ASSESSMENT OF RETIMING TIDAL POWER FROM BAY OF FUNDY USING COMPRESSED AIR ENERGY STORAGE

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1 - INTRODUCTION

1.1 - Objective of Study

The objective of the study is to examine the economic viability of using compressed air energy storage (CAES) to retime cyclic power from the proposed tidal power plant at Site A8. Site A8 is at the mouth of Cumberland Basin in the Bay of Fundy as shown in Figure 1.1.

The study objective was met by preparing prefeasibility level cost and energy estimates based on conceptual arrangements of air compressor, generating plants and underground storage facilities, and relating these estimates to the potential marketability of the retimed power and energy.

1.2 - Terms of Reference

As required by the contract, the work was divided into the following items.

(a) Alternative Tidal Power/CAES Installations.

(b) CAES System.

(c) Marketability

to be included in (d) Report.

A detailed description of the work planned to be included in each item is included in Appendix A. The report has been organized to describe the work carried out for each item with an added section on conclusions and recommendations.

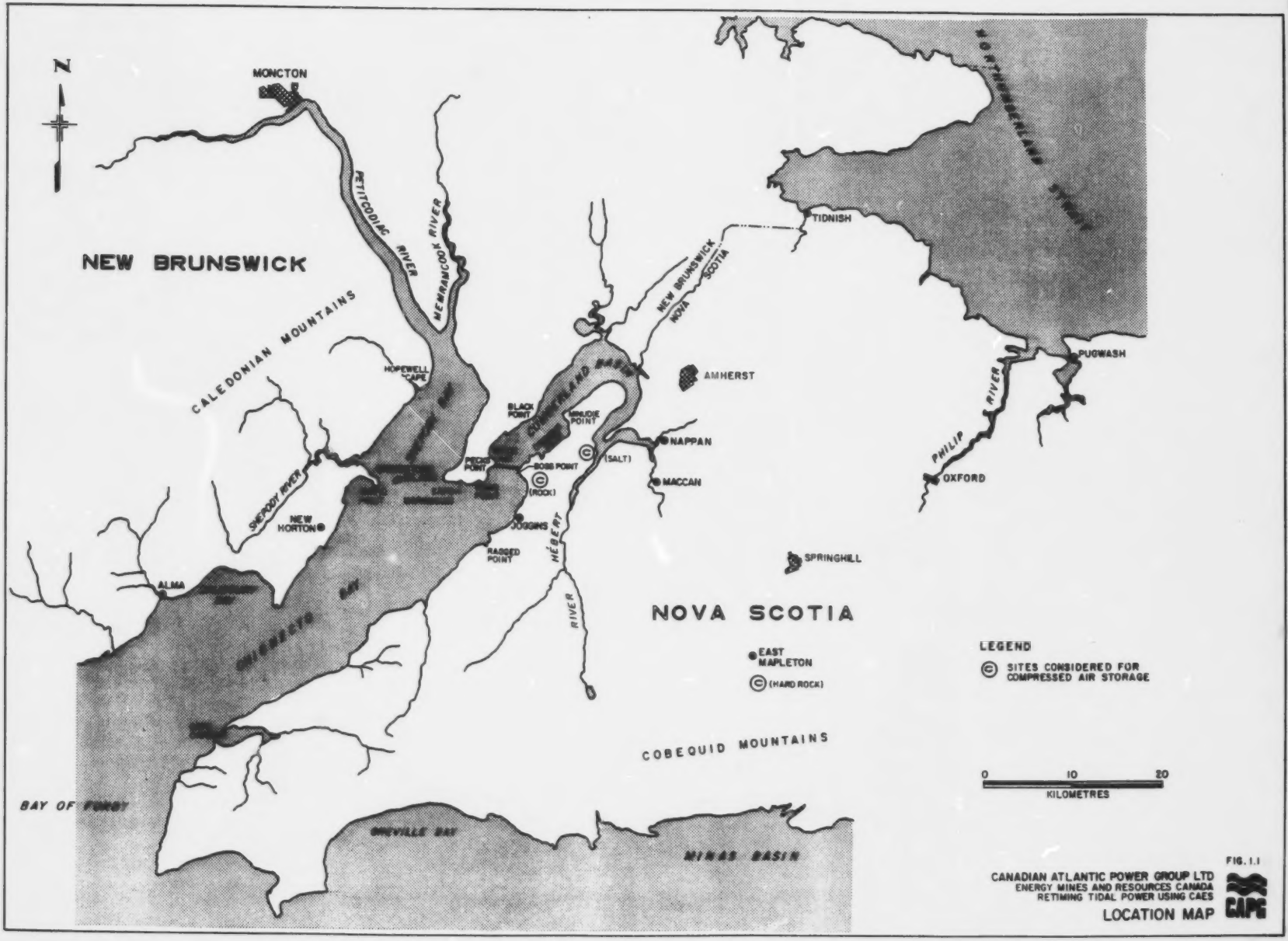


FIG. 1.1

CANADIAN ATLANTIC POWER GROUP LTD
ENERGY MINES AND RESOURCES CANADA
RETIMING TIDAL POWER USING CAES

LOCATION MAP

CAPG

1.3 - Background

The report of the Tidal Power Corporation of December 1985 which provided an overview of the Alcan Aluminium Limited Stage 1 Fundy Tidal Power Study stressed the importance of retiming the cyclic output of potential developments to make tidal energy marketable in both New England and Maritime markets. There were indications that retimed energy output could be considered as a competitive alternative to coal-fired thermal generation at 50% capacity factor.

Since it appeared unlikely that retiming using conventional hydro-electric storage capacity in an interconnected power system could be made available, it was concluded that a dedicated retiming facility should be investigated. Earlier studies had examined alternative methods of hydraulic energy storage with no success but only brief consideration had been given to compressed air energy storage (CAES). Since these studies the first successful commercial application of CAES to an electric power system has been implemented at Huntorf in West Germany. It was decided that in view of this and other technical developments the use of CAES for retiming tidal power should be assessed on the basis of the latest technology available.

From the studies of Tidal Power Corporation it was concluded that the CAES study should concentrate on power to be obtained from Site A8 at the mouth of Cumberland Basin in the Bay of Fundy. Use was made of the estimates of cost and energy output for Site A8 as developed in the earlier studies.

2 - ALTERNATIVE TIDAL POWER/ CAES INSTALLATIONS

2.1 - Basic Considerations

In the study of December 1984 by Alcan Aluminium Ltd. an annual energy output was computed for an optimized tidal power installation consisting of 39 operational turbine generators, each of 34 MW output. This output was estimated by predicting energy output for several tidal ranges and multiplying the results by the appropriate number of annual occurrences obtained from a histogram of tidal ranges.

For the calculation of energy storage requirements in the CAES study it has been necessary to consider how the daily and monthly variations of the tidal ranges could affect the levelized output and the volume of storage required. If only a single tidal range is considered in sizing the storage and level of steady power output then considerable energy would be lost at other tidal ranges. Similarly energy would be lost at weekends if only power output was required during weekdays. Further losses would be caused by variations between spring and neap tides each month. As a result it was concluded that carry over storage would be required to provide enough energy in the form of compressed air storage to last through one month's tidal cycles. Estimates of energy output and storage were computed accordingly, as described later.

The further variation of tidal ranges throughout each year suggested that several levels of storage output should be considered to demonstrate requirements for months containing maximum spring tide, minimum spring tide and mean spring tide. Energy outputs computed for specific tidal ranges were abstracted from the results of the 1984 study and used to simulate the three monthly cycles.

For the purpose of the initial computation it was assumed that all tidal energy is routed through the air storage facility with no direct

link to the power system and no drawing of energy from the system. Levelized output is based on a demand of 5 days/week, 12 hrs/day.

Equipment and storage cavern costs were computed for mean spring tide energy output based on the use of standard available equipment for the CAES plant, and escalated costs for the tidal power turbine generator. For the purposes of the base case estimate the CAES plant is assumed to be separated from the tidal plant. Once the feasibility of a direct coupled gear train is confirmed the potential economy of a direct coupled plant will be examined relative to the base case estimate.

Considerations regarding equipment, layouts and assumptions made are described in the following subsections of the report.

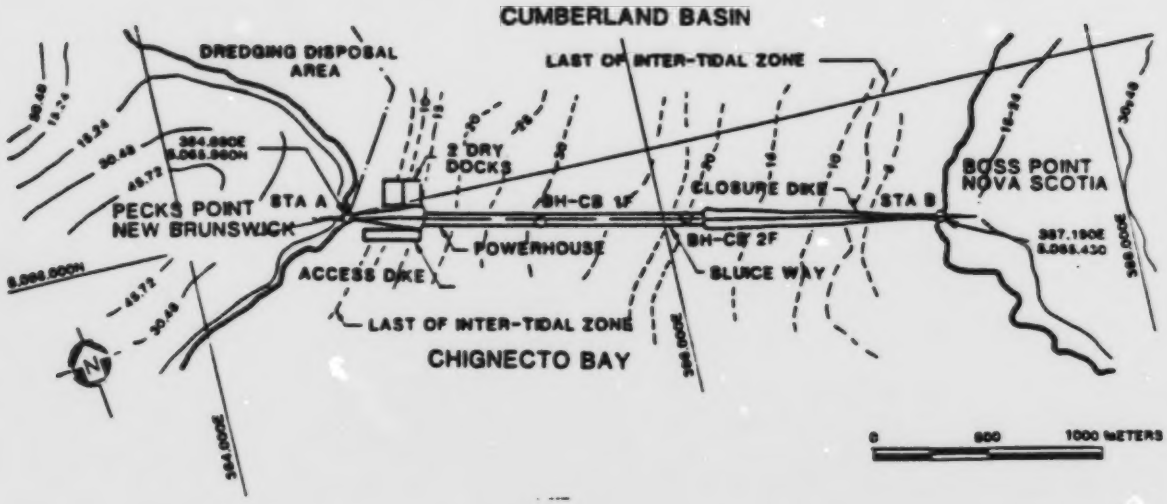
2.2 - Separate Turbine Generator and Compressor Installation

Each of the components required for this type of installation is described in the following subsections.

2.2.1 - Tidal Power Plant

2.2.1.1 - Generating Units

The selection of generating units and types of turbines has been based on the tidal conditions at Site A8 and the general arrangements described in the 1984 Alcan Aluminium Limited, Tidal Power Consultants report. Figure 2.2.1.1 shows the "General Site Arrangement." Plant data are summarized in Table 2.2.1.1.



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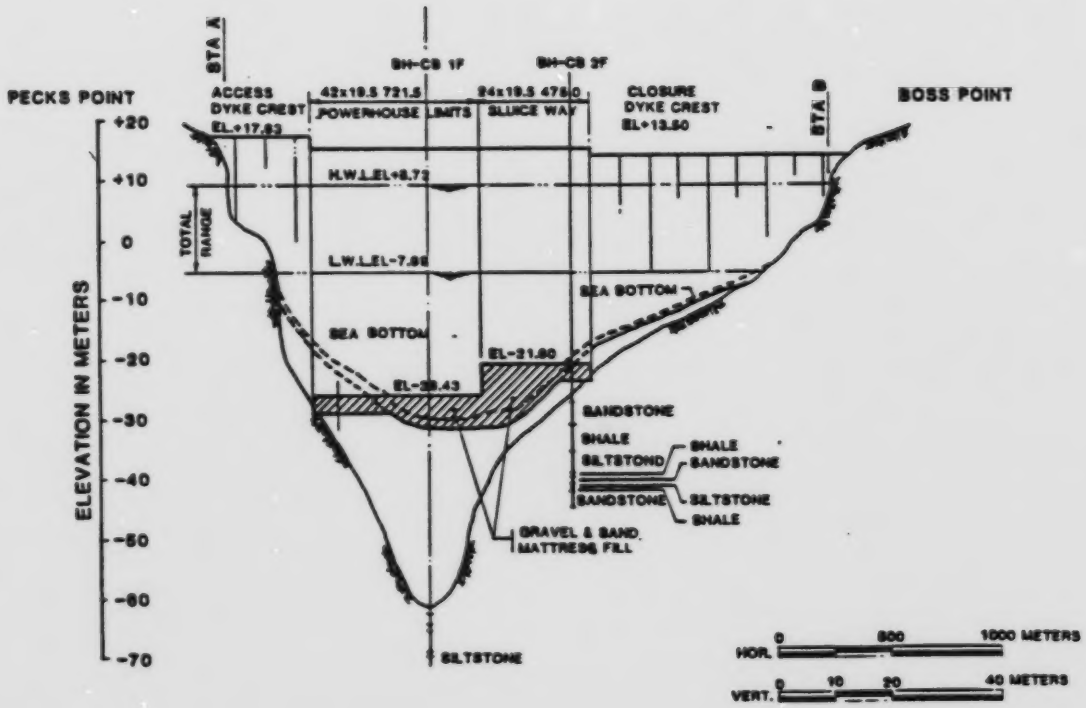


SECTION

GENERAL SITE ARRANGEMENT

FIG. 2.2.11

TABLE 2.2.1.1

TIDAL POWER PLANT DATA

Plant Capacity	1428 MW
Number of Generating Units	42
Active Units	39
Units Under Maintenance	3
Turbine	
Unit Capacity	34,900 kW
Rated Head	9.1 m
Head Range	6.58 to 13.53 m
Turbine Runner Diameter	6.8 m
Type	Horizontal Bulb or Straflo
Rated Speed	66.7 r/min
Generator	
Unit Capacity	35.8 MVA
Power Factor	0.95
Type	Synchronous
Voltage	7.2 kV
Transformers	
Type	OFWF Step Up
Voltage	7.2 to 345 kV
Connection	To 7 Generating Units 6 Operational
Sluice Gates	
Number	24
Width	12.2 m
Height	12.2 m

Notes

1. The plant will be provided with mechanical/electrical auxiliary services which are common to hydroelectric generating stations. These will include compressed air systems for governor, generator brakes, circuit breakers and service air, unwatering and drainage pumps, oil handling, potable and sanitary water systems, ventilation and air conditioning systems, cooling water, lighting, dc battery system, etc.

2. To assure unit security against runway speed after governor failure, each unit will be provided with a hydraulically operated draft tube gate.

3. The powerhouse and sluices and some adjoining sections of the dam are constructed of preformed caissons which will be built in near shore dry docks and then towed into position. Each caisson is then sunk onto prepared foundations. The detailed construction methods proposed are covered in the 1984 report.

Three Canadian and two European suppliers have currently been requested to provide up-to-date budget prices, water passage dimensions and performance data including hill chart for bulb (Figure 2.2.1.2) and Straflo (Figure 2.2.1.3) units.

Data has been requested for variable and fixed rotational speed units as noted in the following table.

The types of units under consideration are

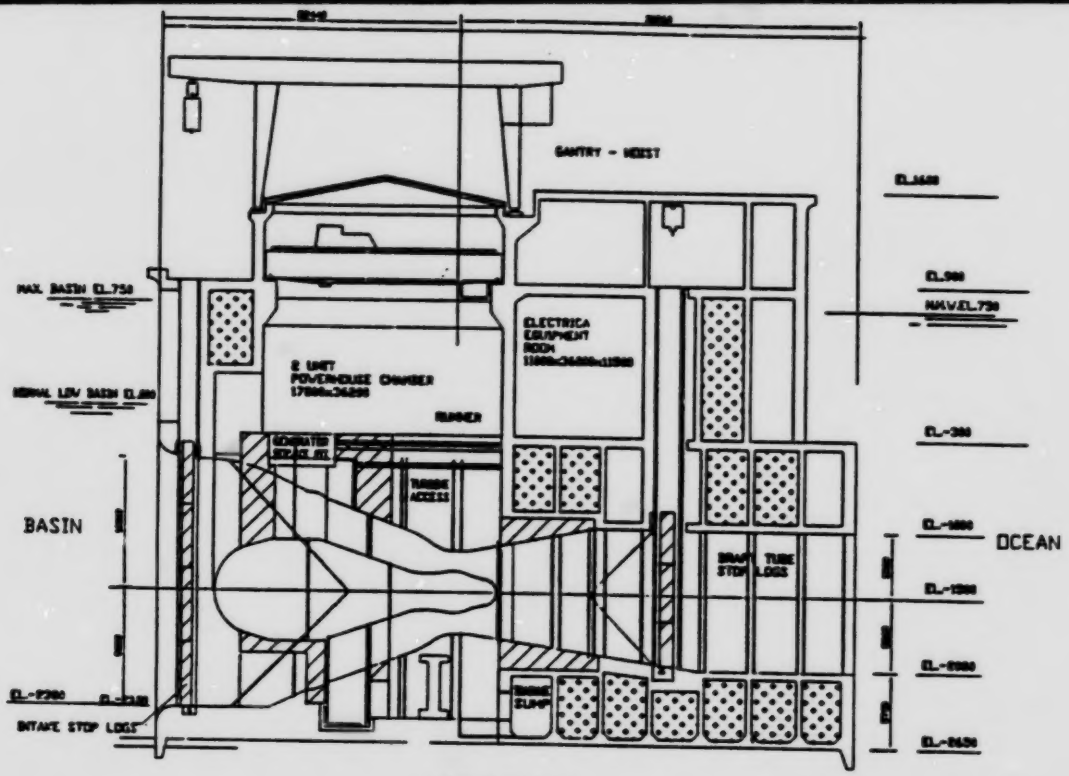
Type of Turbine	Speed		Wicket Gates	Runner Blades	
	Variable	Fixed		Fixed	Adjustable
1. Straflo	X		X	X	
2. Straflo		X	X	X	
3. Bulb	X		X	X	
4. Bulb	X		X		X
5. Bulb*	X		No		X
6. Bulb		X	X		X
7. Pit	X		X	X	
8. Pit	X		X	X	
9. Pit	X		No		X
10. Pit		X	X		X
11. Pit or bulb with direct compressor drive					

* Bulb unit with outlet control gate.

2.2.1.2 - Tidal Characteristics

General

The following Sections 2.1 to 3.7 have been extracted from the 1984 TPCL report and are included here for pertinent background.



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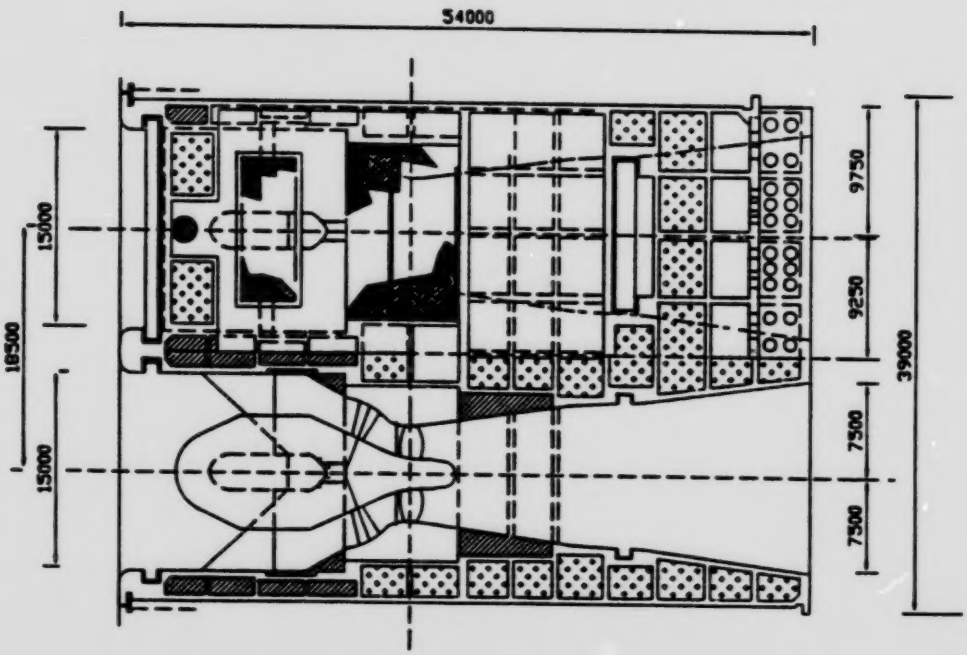
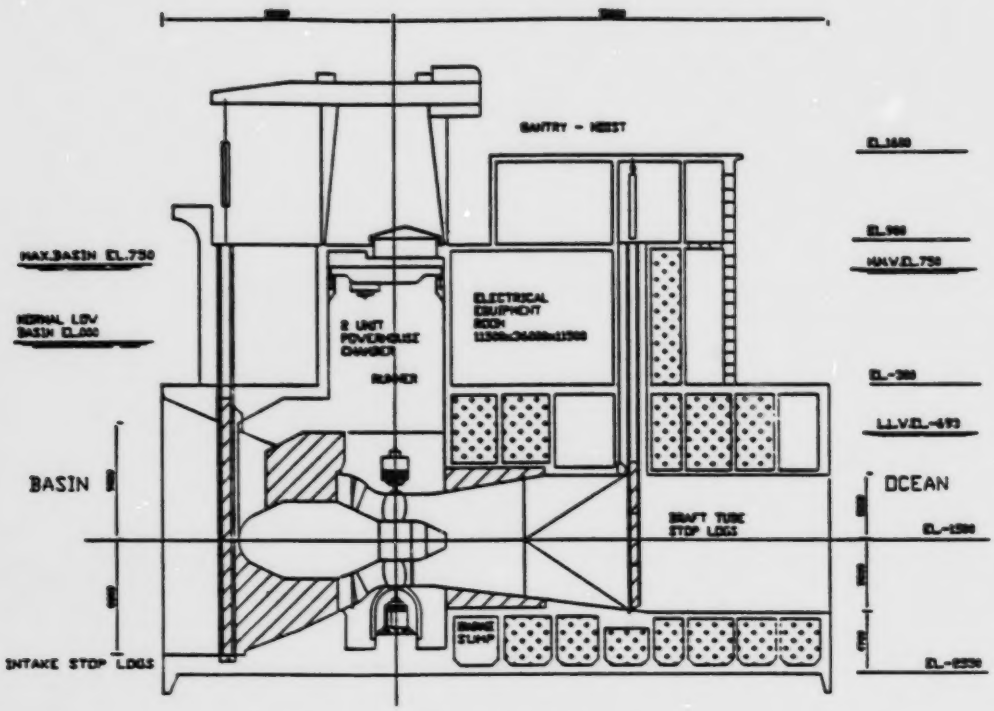


PLAN

BULB GENERATING UNIT

FIG.2·2·1·2



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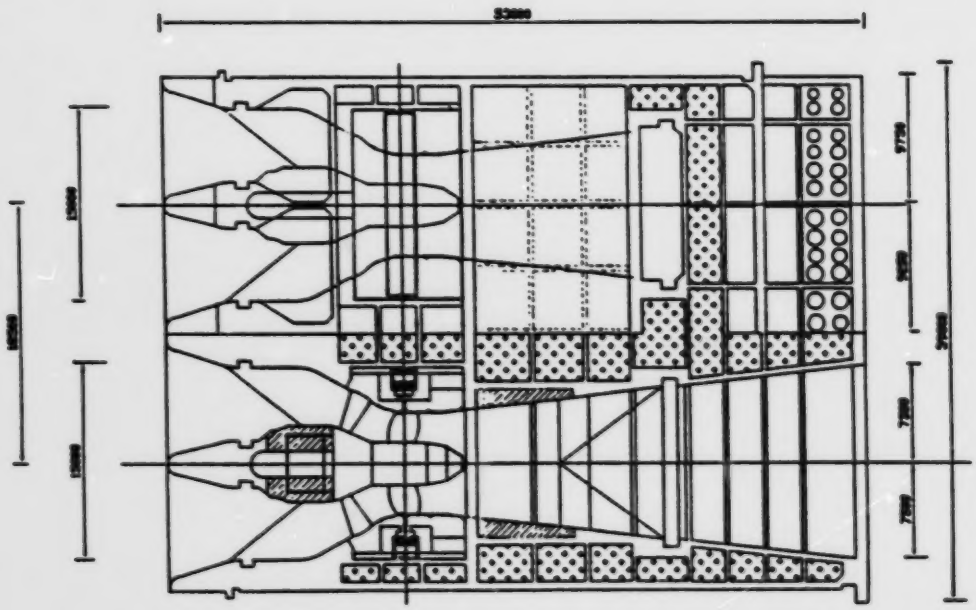


PLAN

STRAFLO GENERATING UNIT

FIG. 2.2.13

Based on their size and regularity, the Fundy tides are well suited to the development of tidal power. The magnitudes of the natural tide range and natural energy available from the selected Cumberland Basin, Site A8 are listed below.

Site	Tidal Range Maximum (m)	Tidal Range Minimum (m)	Natural Energy 10^2 kWh/year
A8	13.53	6.58	14.4

As a result of the barrage construction, natural tidal ranges will decrease at the site. Maximum and minimum design water level conditions will be influenced levels by meteorological conditions.

By definition, "Natural Energy" is the theoretical amount of energy produced by flow through a set of imaginary 100% efficient turbine generators, filling a tidal basin from minimum to maximum tidal level at the instant the tide outside the tidal barrage is at its maximum level and by emptying the tidal basin by flow through such turbines at the instant the level of the tides outside the barrage is minimum.

2.2.1.3 - Turbine Operation

(a) General

During the generating phase, the water passing through each turbine must be regulated so that the basin is emptied at the optimum rate. The flow control strategy might be to regulate the turbine for maximum efficiency operation, at the available head, or to regulate the turbines to produce maximum

power for the available head. The optimum control begins at maximum efficiency and ends at maximum power as the head increases. In the intervening time, the turbines will be regulated according to a solution used during the 1977 Fundy studies.

In practice, the 1977 calculus of variations solution is only required with a turbine having a large variation of discharge between maximum efficiency and maximum power output. This is the case with variable speed operation. In other cases, regulation along the maximum power output curve is satisfactory.

Turbine operation is modified according to the following constraints during the power output analysis.

- cavitation limitation
- generator capacity limit.

These constraints call for regulating the turbine discharge. This can be achieved by reducing the wicket gate opening or adjusting the pitch of the runner blades to operate the unit at a point on the hill chart where cavitation is not a problem or to where the power produced is within the capabilities of the generator.

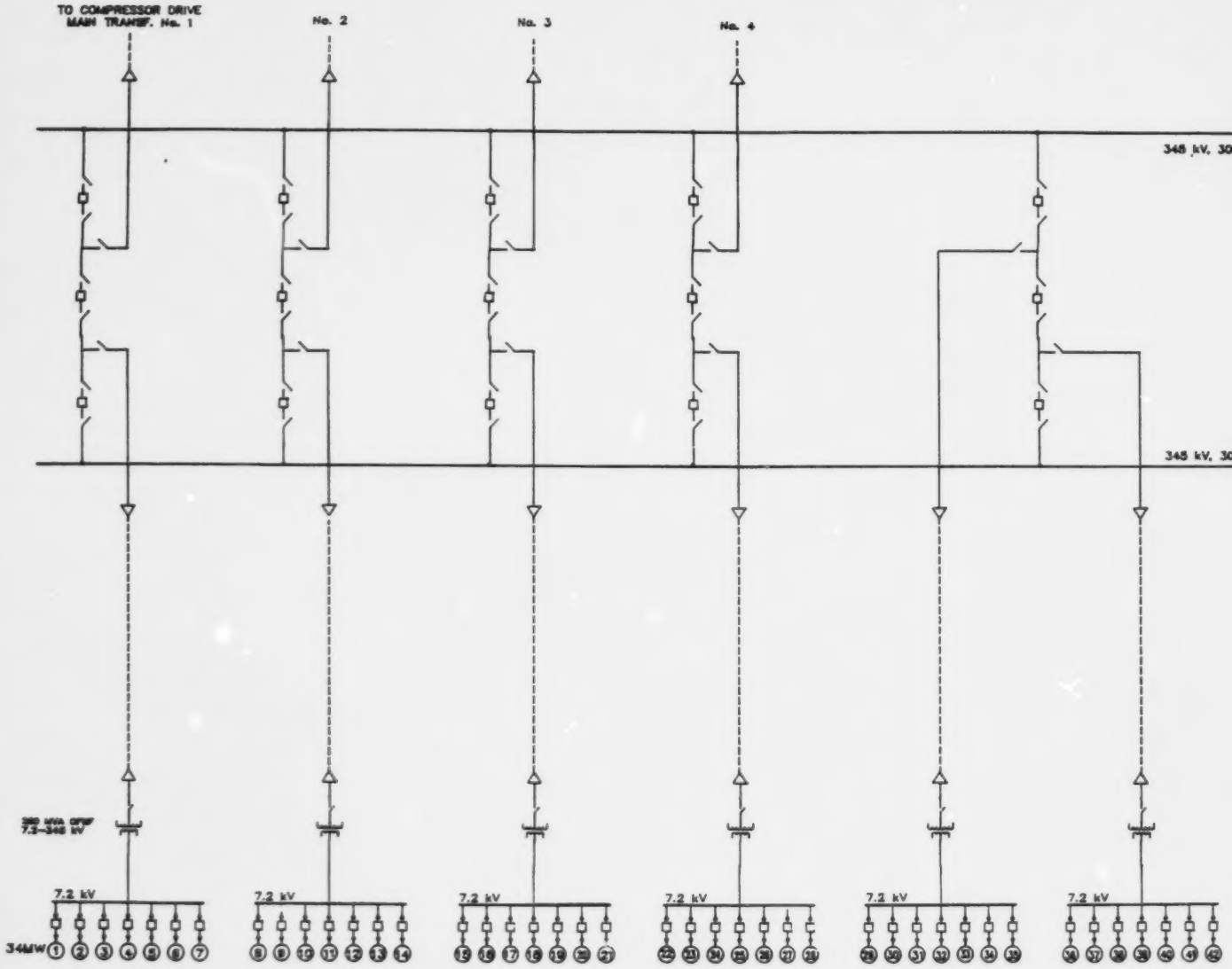
Incorporation of the cavitation constraint in the computer power analysis model is important since in common with other sites for tidal power barrages the depth of water available at Site A8 is limited. In consequence, the elevation of the turbine centerline is such that at low tide when the turbine head is

greatest the submergence of the runner is insufficient for normal operation. However, the program shows that because these conditions only exist for a short time, throttling the turbine to a safe discharge results in minimal cavitation damage and loss of energy. Selection of the optimum rotational speed, rather than a safe speed dictated by the worst condition, is possible.

In order to model the turbine operation accurately, particularly when constraints are encountered, a dimensionless turbine efficiency hill chart model was input for all computer runs. In this way, at all times in the computer simulation, turbine efficiency was read directly from the hill chart model. The model represented results of efficiency tests of a model turbine and water passage under various conditions of head, flow and rotational speed. Two adjustments are necessary when these results are applied to prototype conditions.

- To allow for the scale effect between model and prototype use efficiency the Hutton formula was used.

- In calculation of power produced allow for intake and exit losses to determine turbine operating head and use hill chart to determine turbine efficiency.



BAY OF FUNDY TIDAL POWER
POWERHOUSE ONE LINE DIAGRAM
FIXED SPEED GENERATION

FIG.2.2.1.4

The calculation of energy production considered a generator efficiency of 95%. Provision was made to calculate and deduct transmission power losses from the "at site" production figures.

(b) Fixed Speed
Turbine Operation

In this case, turbines are operated at a constant rotational speed in the conventional manner - they may, or may not, be synchronized to the receiving system, depending upon whether ac or dc transmission is adopted.

Discharge regulation of fixed speed turbines may be achieved by means of adjustable distributor wicket gates or by adjustable runner blades or both. For tidal power applications, the volume of discharge is almost as important as efficiency. The results of the 1977 Fundy studies and the 1981 studies show that double regulation by distributor wicket gates and runner blades is unnecessary. Single regulation may be achieved by using wicket gates with fixed runner blades or by a unit without wicket gates and with variable pitch runner blades. The latter type of unit achieves somewhat higher efficiencies over the full head range. It requires a downstream gate to perform operational and emergency functions. These functions can be performed by variable opening wicket gates and hence a flow control regulating gate is not essential. Consequently, for the 1984 studies, the fixed blade unit with distributor wicket gates was adopted.

Optimization of the turbine performance requires selection of four parameters which are

- rotational speed (rpm)
- generator capacity limit (MW)
- turbine runner blade angle(s)
- turbine wicket gate angle (opening range) - if selected.

Power characteristics are dependent upon the above and the basic model turbine efficiency shown on the hill chart. An optimization of these parameters was performed in 1984 for a 31 MW, fixed speed bulb unit, current unit size is 34 MW for Site A8. The bulb unit generator is housed just upstream of the turbine in the bulb. The Straflo unit features a rim type generator which is built around the periphery of the turbine runner and forms the runner discharge water passage surface. The generator rotor and the turbine runner rotate as a unit. The generator of a Straflo machine is more readily accessible for maintenance than the bulb unit generator.

(c) Variable Speed
Turbine Operation

The concept of variable speed operation in the case of CAES requires an ac-dc-ac converter inverter system to deliver ac power to the compressed air station and local grid. Further ac-dc conversion is required with a dc transmission link to the load center. DC transmission frees the tidal plant generating units from a fixed frequency of generation within certain constraints, turbine speed and consequently generator frequency, can be allowed to

vary. Variation of turbine speed can be used as a form of regulation to control discharge or optimize efficiency of operation.

For variable speed machines, triple regulation is possible in principle but as is noted in the 1984 report, does not yield sufficient economic benefits to offset the additional cost. Only units with fixed runner blades and wicket gates and units without wicket gates, with adjustable runner blades and variable speeds were considered acceptable.

The variable speed unit without wicket gates and adjustable runner blades requires a draft tube control gate for start up and routine and emergency shutdown of the machine. The electrical inverter converter system, required for variable speed units, is an additional cost.

For the above reasons, consideration should be given to three types of variable speed units.

(i) Double regulated with adjustable wicket gates and fixed runner blades.

(ii) Single regulated without wicket gates using adjustable runner blades.

(iii) Single regulated without wicket gates with fixed runner and downstream gate.

As a measure of the size of generator required for variable speed operation, the maximum power generated and the maximum torque (the ratio of power/speed) are utilized. With unit (i) operating, power and torque can be constrained within specified limits in a similar way to the fixed speed case. With types (ii) and (iii), however, it is possible to limit power and torque and operate to avoid cavitation. A generator must be provided which is designed for the worst condition experienced.

(d) Turbines - Types (i) and (ii)

These types of unit have a wide variation of discharge over the power range. Computer estimates of energy were based on type (i) units and took this aspect into account to optimize the discharge regulation. For each discharge setting the facility to vary speed allowed the computer program to search the hill chart to find the speed to give the optimum efficiency, thus maximizing power output.

Optimization for this type of operation required the selection of the optimum runner blade angle and generator rating for maximum power and maximum torque.

(e) Turbines - Type (iii)

This turbine type offers the potential for substantial cost reduction in manufacture since there are no wicket gates and runner blades are fixed and a great deal of accurate machining is eliminated. Because of these simplifications, it should be possible to improve deliveries for earlier plant

completion. As a result, counterbalancing the savings in turbine mechanical parts cost are the additional costs incurred by the provision of a downstream gate to shut off flow and control units at start up. To obtain energy output comparable with single regulated fixed speed machines it was found that a greater generator rating is required.

With Type (iii) machines, rotational speed will be controlled according to a predetermined pattern by loading of the generator. Operation to avoid cavitation can be achieved by slowing of the machines thereby reducing discharge. In so doing, the generator torque is increased.

For Types (i) and (ii) operation optimization requires the selection of distributor opening and blade angle, for each combination the greatest tidal range will determine the generator rating. There is a limited scope for reduction of generator rating by reducing the maximum head which develops on the highest tidal ranges. This can be achieved by either starting generation earlier or limiting the level to which the basin is filled by the sluices or a combination of both.

2.2.1.4 - Electrical System and Major Equipment

(a) Fixed Speed Generation

The main equipment, its rating and interconnection is shown in Figure 2.2.1.4.

The forty two (42) turbine generators would be synchronous, fixed speed units of the bulb type. Each unit is rated 34 MW, 69.2 rpm (104 poles), 0.95 power factor, 7.2 kV, 60 Hz. The generator voltage of 7.2 kV has been selected to keep the unit size within the runner diameter of 6.8 m.

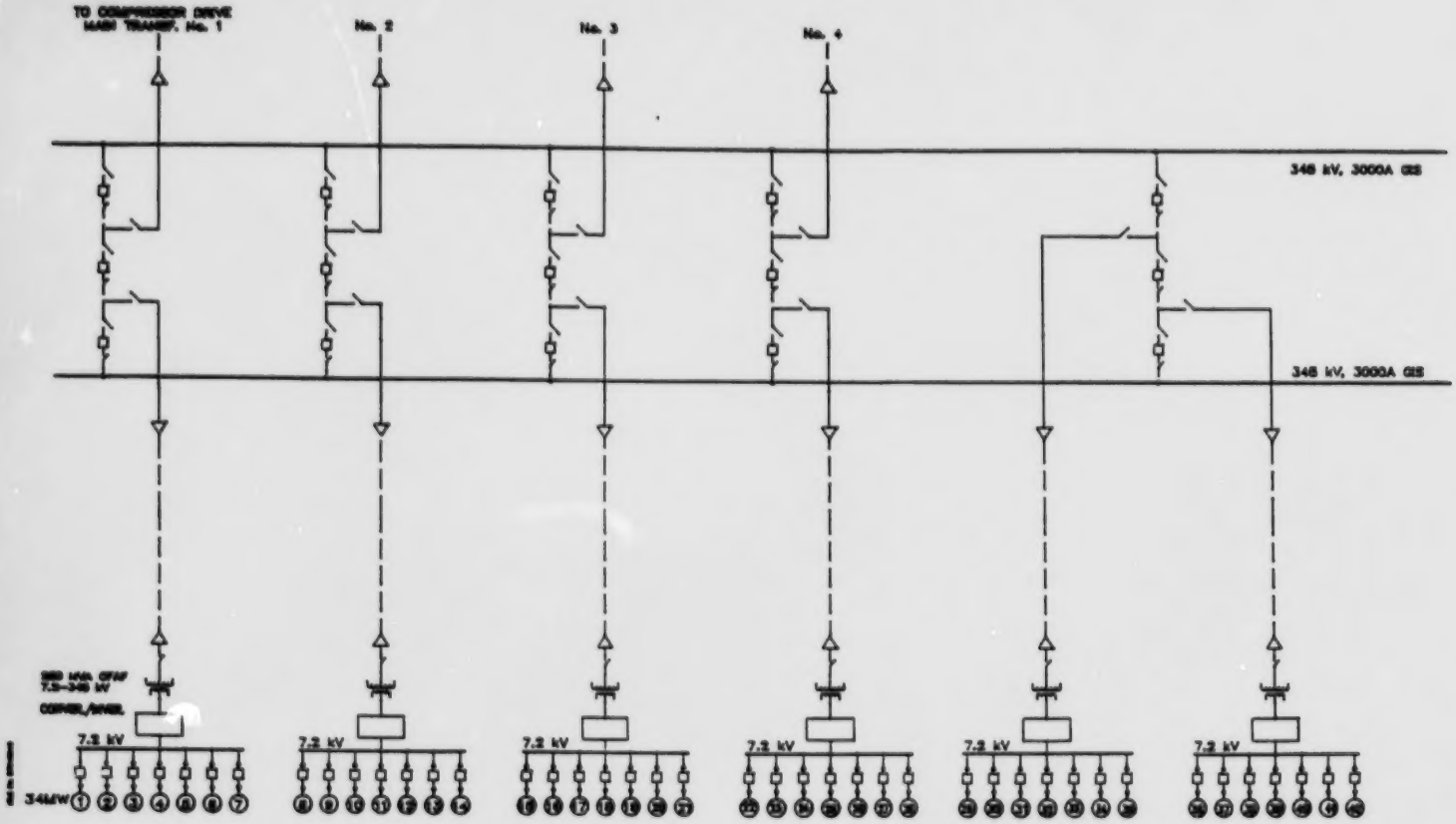
Each unit is provided with a dedicated circuit breaker. A group of seven units in parallel will be connected to a 3 phase 250 MVA OFWF, 7.2 kV - 345 kV step-up transformer. A total of six groups is provided.

In view of the high fault current for a fault at generator terminals, the generator circuit breakers will be used for synchronizing and isolating the units and not for fault clearing. In the event of a fault, the field breakers of all the units in one group (7 units) and the H.V. breakers will be tripped. This will be more economical than using individual fault interrupting generator breakers.

(b) Variable Speed Generation

The main equipment, its rating and interconnection is shown in Figure 2.2.1.5. The scheme is basically the same as that of fixed speed, the only difference being addition of converter/inverter at 7.2 kV.

The forty two (42) turbine generators would be synchronous, variable speed units, either bulb type or Straflo type. The operating speed will be 35-70 rpm. The unit rating is same as for the fixed speed except the frequency and voltage, which will be variable.



BAY OF FUNDY TIDAL POWER
POWERHOUSE ONE LINE DIAGRAM
VARIABLE SPEED GENERATION

FIG.2.2.1.5

A converter/inverter system will provide 60 Hz power. The 60 Hz power output from converter/inverter system will be stepped-up to 345 kV through step-up transformers. The effect of using fixed speed turbine generators and ac transmission to the compresser plant is discussed later in Section 4 of the report.

(c) Power Delivery to Shore

The method of carrying power at 345 kV to the shore will depend upon the distance from the power station.

For a distance of less than 3 km, oil-filled cables will be utilized to interconnect generator step-up transformers to the 345 kV SF_6 gas insulated switchgear located in the main substation at the shore.

For a distance of greater than 3 km, a 345 kV SF_6 gas insulated switchgear will be installed in the powerhouse. The six step-up transformers will be connected to the switchgear bus and two feeders, each rated for full plant capacity, comprising of SF_6 gas insulated bus duct which will carry the power to the main substation.

2.2.2 - CAES Plant

2.2.2.1 - Overview

The main deficiency of tidal power is the fact that it is cyclic and available only intermittently, and is therefore of little use in meeting the demands of an

electrical supply system having regular and predictable requirements to supply power.

CAES was originally envisaged as a means of utilizing off-peak electricity generation to store energy for later release and electricity generation at peak demand periods. Most, if not all, the emphasis on the utilization of CAES has revolved around this off-peak storage and on-peak generation philosophy but the process is equally applicable to the retiming of tidal power. The following discussion describes the basic concept of compressed air energy storage and its modification for use in tidal power generation plant.

CAES is a technology which converts electrical or mechanical energy into stored pneumatic energy by means of a compressor, for later release through a gas turbine to generate electrical power. The principle of the air storage plant is therefore based on the idea of separating the compression and expansion processes of a conventional gas turbine and storing the compressed air. In a conventional gas turbine the two are physically connected with the compressed air passing directly into the gas turbine combustors.

The layout selected for a typical CAES plant is shown in simplified diagrammatic form in Figure 2.2.2.1. It consists basically of a compressor section, a combined motor/generator, and a gas turbine section with fuel combustor. Clutches are located between the compressor, turbine and motor/generator sections, such that the compressor can be driven by the motor separated from the turbine, while the turbine can drive the generator separated from the compressor.

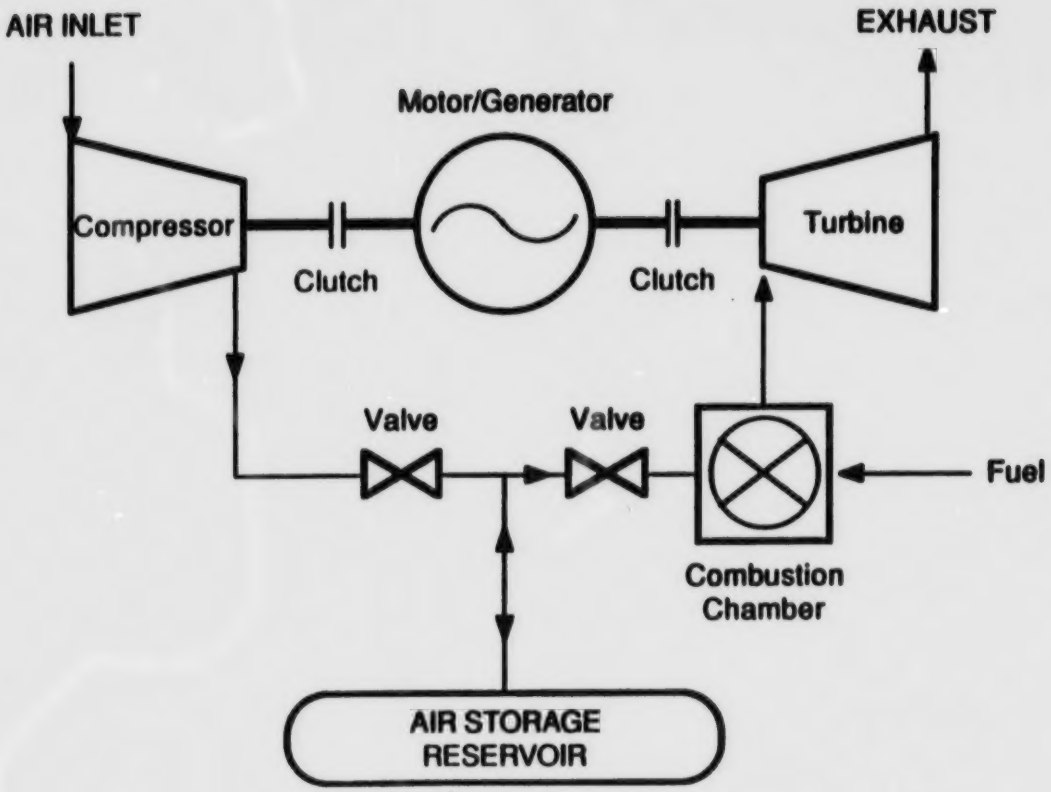


Figure 2.2.2.1

Schematic Diagram of a CAES System

In operation, ambient air is compressed using off-peak electrical power to drive the compressor with the motor, and the compressed air is fed to the storage cavern. When electrical power is needed, the compressed air is fed from the storage cavern through a control valve into the combustion chamber where, after being heated by the combustion of a hydrocarbon fuel, it passes to the gas turbine. Here, the heated compressed air expands through the gas turbine to atmosphere and provides the energy for the turbine to drive the generator and produce electrical power. This is a simplified description of the process cycle.

The air storage cavern design is influenced by the available geology in the area of the plant site. There are several possible ways to obtain caverns for air-storage facilities. Depleted oil and gas wells may be used, defunct mines, aquifers, natural caverns, man-made excavations and leached caverns are all possibilities. For the CAES installation at the Bay of Fundy which required large storage volumes, consideration has been given to air storage in caverns in a local salt formation which can be solution mined and in hard rock formations.

Evaluation and selection of the air storage caverns are discussed later in this report.

For the CAES plant separated from the tidal power turbine generators the arrangement may consist of the compressor, motor/generator and turbine with clutches as described earlier, or there may be compressor trains driven by a separate electric motor, and gas turbine with generators only, there being no physical linking of the two. For the base case the separated compressors/motors and gas turbines/generators are selected as this arrangement

allows a number of smaller compressor units to be switched in or out in phase with the level of available tidal power, while allowing a smaller number of larger gas turbines to be utilized for power generation. The various reasons behind direct matching or not matching of compressors and turbines is also discussed in Section 2.2.2.3. This concept allows the use of standard equipment without extending the state of the art.

2.2.2.2 - Compressors and Air Intercooling

The simplified flow diagram presented in Figure 2.2.2.1 omitted much of the detail which would be found in the flow circuit of an actual plant. Figure 2.2.2.2 shows the flow diagram for such a plant, that of the successful Huntorf project in West Germany.

It can be seen that there is more than one stage of air compression machinery, coolers are required to cool the air between compression stages and prior to injection into the cavern, and two combustors and turbine elements are utilized.

The compression of air takes place under essentially adiabatic conditions with no gain or loss of heat in each stage of the compressor. The temperature rise which accompanies compression can be calculated readily, and as an example of the high temperatures resulting from compression of air, adiabatic compression from 14.7 psia, 100 F to 735 psia would result in a final air temperature of 1180 F. In addition, heat is added due to machine inefficiency, and with an 85% compressor efficiency the discharge temperature would be raised to 1360 F. Not only does this raise problems with structural materials,

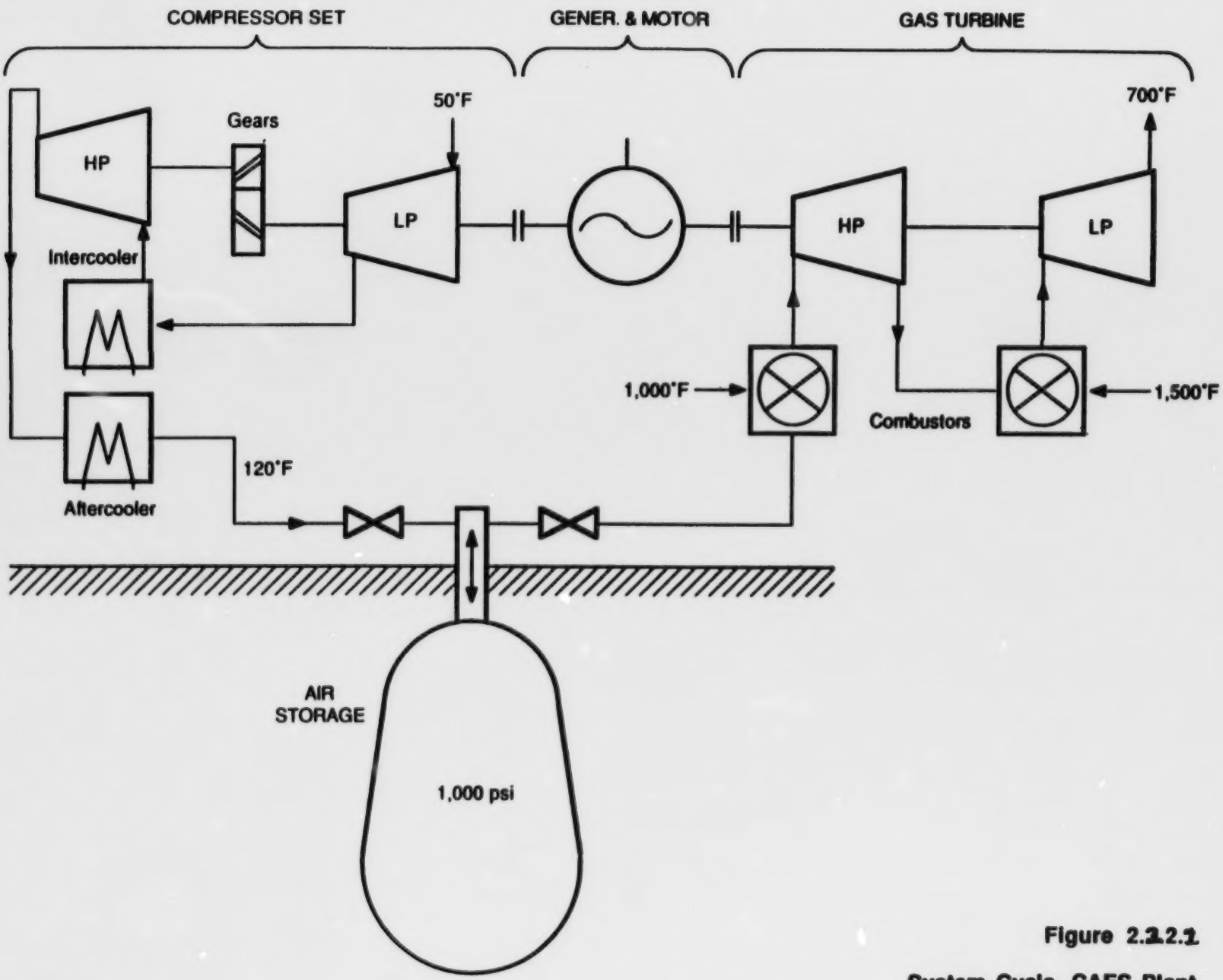


Figure 2.2.2.1

System Cycle, CAES Plant

seals and lubricants for the machine, but the energy required is greater than if the air was cooled between compressor stages.

Using the same inlet conditions of 14.7 psia, 100 F but with intercooling between two stages of compression, the discharge temperature can be reduced drastically. For a first stage compressor ration of 10:1, from 14.7 psia to 147 psia, the temperature would be around 690 F, and if intercooling to 100 F is carried out prior to second stage compression the final temperature after compression to 735 psia would be 500 F. Thus, with one stage of intercooling the discharge temperature is substantially reduced, and with additional intercoolers it could be reduced still further.

The power required to compress air can also be significantly reduced by intercooling. This can been seen from the formula for compression work which is

$W = 2.054\ (k/k\text{-}1)\ T1\ [P_2/P_1)(k\text{-}1)/k\ \text{-}1]\ HP/10^6\ ft^3$ of air where T1 = air inlet temperature, P_2/P_1 is compression ratio

and is thus directly proportional to inlet air temperature. While the pressure ratio per compression stage has an effect on the amount of power that can be saved with intercooling, typically 25% can be saved with two stage compression and intercooling, and 31% with three stage compression and two intercoolers.

Following the final stage of compression the air must be cooled further in an aftercooler. The purpose of this is to minimize the effects of thermal gradients in the walls of the cavern structure. All of the heat removed from the air in the intercoolers must be discharged via a cooling water system to a heat sink, which, if appropriate, could be a body of water such as the Bay of Fundy. The environmental implications of this will have to be assessed. A significant amount of heat has to be removed and large cooling water lines are required in the plant.

The compression machinery, whether for the direct mechanical drive concept or the electrically driven system units would follow the same lines of selection. The layout used at Huntorf consists of an axial flow low pressure compressor and a centrifugal flow high pressure compressor. The axial flow compressor is a large volume flow machine operating at lower pressure and rotational speed, whereas the centrifugal compressor handles the lower volumetric flow leaving the low pressure compressor, and boosts it to the maximum pressure in the system prior to entering the air into storage. Typical speeds of rotation for the two types of machines would be 3600 rpm for the axial flow compressor and 9000 rpm for the centrifugal compressor, the speed increase being achieved by mechanically linking the two compressors by a step-up gearbox or speed increaser.

The compression system proposed for the tidal power plant will be that commonly proposed for current CAES plant, namely, an axial flow low pressure compressor with an intercooler between low pressure and high pressure compressor, two stages of intercooling of the air passing through the high pressure compressor, followed by an

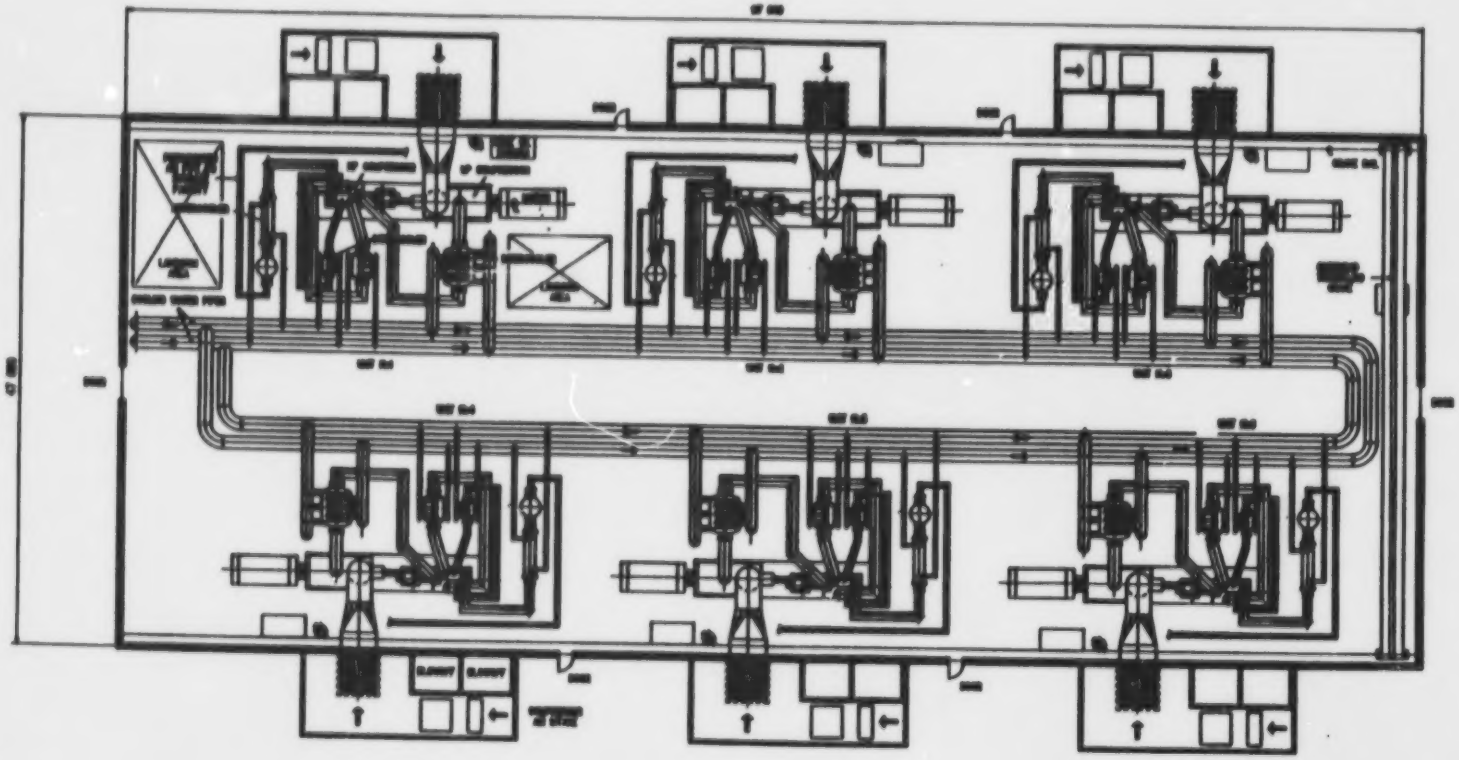
aftercooler so that the air going into storage is at around 140 F. When further data is received from suppliers it will be included in the report.

Each compressor drive will be a synchronous motor, rated 60 MW, 3600 rps, 13.2 kv, 60 Hz, 1.0 power factor. Power at 345 kV will be stepped down to 34.5 kV through 375 MVA, 345- 34.5/34.5 kV three winding transformers. The 60 MW, 13.2 kV drive motor with a 34.5-13.8 kV captive transformer will be connected to the 34.5 kV bus. Each motor will be started through a variable frequency starting system, synchronized and transferred to its own breaker. A group of six motors and one variable frequency starting system will be connected to one 34.5 kV bus. A total of four such buses are provided. The 34.5 kV switchgear will be indoor metal-clad with draw-out SF_6 gas insulated circuit breakers.

A typical arrangement of compressors is shown in Figure 2.2.2.3 with the electrical one line diagram in Figure 2.2.2.5.

2.2.2.3 - Gas Turbines and Combustors

The power generation system contains the gas turbines, generators, combustors and associated air inlet and exhaust ducting and air flow regulating valves.

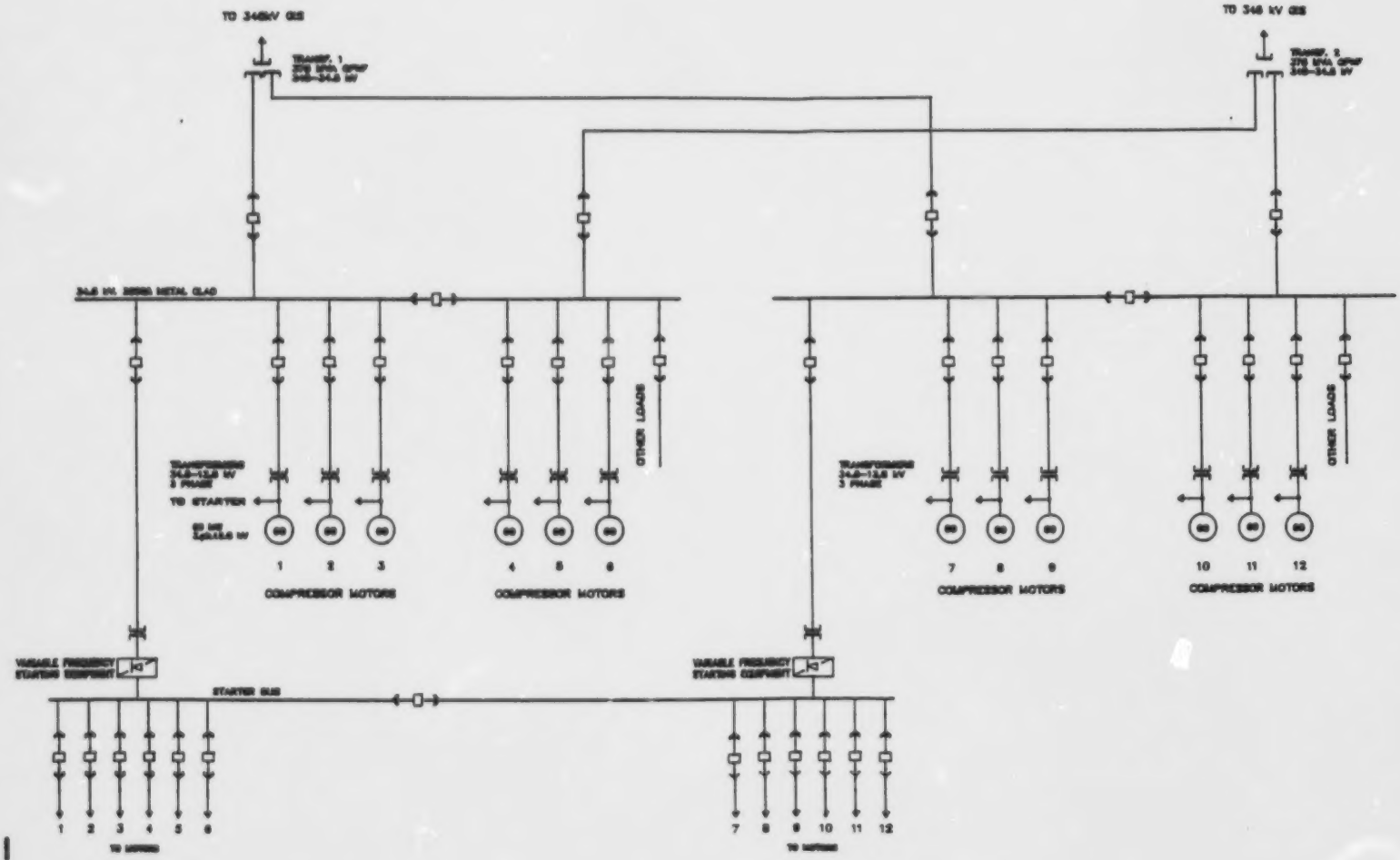


ELECTRICALLY DRIVEN
6-60MW COMPRESSOR
TOTAL PLANT 24-60MW
(BASE CASE)

Fig. 2.2.2.3

C.A.P.G.

ENERGY MINES AND RESOURCES CANADA
RETIGNI TIDAL POWER MINING CASE
TYPICAL COMPRESSOR PLANT



NOTE: SIMILAR ARRANGEMENT FOR COMPRESSORS 13 to 24

BAY OF FUNDY TIDAL POWER

ONE LINE DIAGRAM

COMPRESSED AIR SYSTEM

FIG.2.2.2.5

Geological conditions and the cost of mining a storage cavern are major factors in determining how the air is released from storage and supplied to the gas turbine. In the compensated type of cavern the pressure of the air is kept constant by a water column during discharge of the air, and the gas turbine receives air at essentially constant pressure during the entire discharge cycle. In the variable pressure system, also referred to as the sliding pressure or uncompensated mode of operation, the pressure in the cavern reduces during the operating cycle of the turbine. Not only does this require a much larger volume of cavern, but the air must be controlled to produce a constant pressure at the turbine inlet. This is necessary because the optimum design of a turbine requires that the pressure ratio across it remains constant.

Investigations into the optimization of CAES plant have established a storage pressure range over which the relationship between useful work produced and compression work done is at its most economic value. This pressure range was found to be between 46 and 66 bar (667 and 957 lbf/in.^{2}). Below about 40 bar (580 lbf/in.^{2}) the storage volume and the turbine are larger and the manufacturing costs higher, and above this pressure the specific fuel consumption is lower but the investment costs are considerably higher.

The pressure limits selected for the tidal power CAES plant are therefore 650 and 1000 lbf/in.^{2}.

The essential differences between a conventional gas turbine generator and a gas turbine generator for a CAES plant are twofold. Firstly, in a conventional gas turbine, approximately 60% of the power generated by the

turbine is required to drive the compressor and only 40% is converted to electrical power. In a CAES plant the air compression occurs independently of power generation and therefore all of the turbine power is utilized for power generation. In effect this means that the turbine size for a given generator output is considerably smaller in a CAES plant. Secondly, the turbine inlet pressure on a CAES plant is considerably higher than for a conventional gas turbine.

The air pressure developed in the compressor section of a conventional gas turbine is typically 150 lbf/in.^{2}, and this is the maximum inlet air pressure to the turbine. In a CAES plant the turbine inlet pressure would typically be 600 lbf/in.^{2}, and prior to the first CAES plant at Huntorf this was an unproven piece of equipment.

The design and development of such a machine is a straightforward extension of present technology, however, provided the inlet temperature does not exceed 1000°F. Since steam turbine operation is analogous to these conditions, this technology can be used, and in fact the Huntorf turbine high pressure section was designed according to steam turbine practice. Additionally, in the process industries, hot gas expanders are in use to recover heat from hot exhaust gas for applications such as compressor drives, and are based on a technology that can be utilized for CAES turbines.

The utilization of existing turbine technology, and the need to utilize as high a gas temperature as practical to achieve high efficiency, has resulted in a gas turbine layout consisting of a high pressure, moderate temperature turbine coupled to a moderate pressure high temperature turbine.

Typical conditions would be HP turbine inlet air pressure of 600 lbf/in.^{2} heated to 1000°F in a gas fired combustion, the turbine exhausting at 150 lbf/in.^{2} into a second combustor which provides LP turbine inlet conditions of 150 lbf/in.^{2} and 1500°F. The LP turbine would be a conventional gas turbine unit operating at normal gas turbine conditions.

A fundamental decision must be made in the selection of the turbine design philosophy, that being whether or not the low pressure compressor is matched to the turbine. This would be necessary if the unit was for any reason to be operated in the manner of a conventional self-contained gas turbine unit. The advantages of this are discussed later and can be summarized as follows.

- The system may be started up as a normal gas turbine without a large and costly controller for the generator.

- The system may be operated as a conventional gas turbine peaking unit if the air storage caverns were not fully charged.

There is, however, possibly a more compelling reason why they should not be matched. If they are not matched, the charging flow is independent of the power cycle. In the case of the tidal power CAES, the cycle of intermittent charging in phase with the ebb tide is not compatible with the demand of the power system.

The study has shown that an arrangement of smaller compressors in greater numbers is more appropriate to the variable output available from the tidal turbines, in conjunction with larger sized gas turbines for economy of

scale, operation and maintenance. The system cycle diagram is the same as that in Figure 2.2.2.2 except that the motor and compressor would be separated from the gas turbine and generator. There are more compressors than turbines. For the base case it has been assumed that there is no intention to operate the plant as a means of generating peaking power using hydrocarbon fuel as the energy source.

One further item of consideration is whether or not to use a regenerator (also referred to as a recuperator) to recover heat from the LP turbine exhaust gases. In the interests of simplicity, the Huntorf plant did not utilize a regenerator, but the current thinking on CAES plants is to use a regenerator to utilize the turbine exhaust heat, with a consequent reduction in the amount of fuel burned. It is likely that future plants will include regeneration.

The regenerator is a component which is still a subject of research and development. It is required to contain air at up to 1000 lbf/in.^{2} pressure while at the same time being subjected to rapid thermal transients. It, therefore, has yet to be proven in CAES service. However, the potential gains are a considerable saving in the amount of fuel burned, showing a potential reduction of about 30% in turbine heat rate BtU/kw.h. The turbo generators will be synchronous machines, each rated 105 MW, 3600 rpm, 0.85 power factor, 13.8 kV, 60 Hz. Each generator is provided with a dedicated circuit breaker and a group of two units in parallel will be connected to a 240 MVA, OFWF, 13.8 kV-345 kV two winding step-up transformer. A total of four (4) banks will be provided. Oil-filled cables will be utilized to connect the step-up transformers to the 345 kV SF_6 gas insulated

switchgear located in the main substation. The 60 Hz power generated from these units will be fed into the EHV grid.

A typical arrangement of gas turbines is given in Figure 2.2.2.4 with the electrical one line diagram in Figure 2.2.2.6.

2.2.3 - Base Case CAES System

To facilitate the sizing of facilities and preparation of cost estimates, it was necessary to select a base case or typical CAES installation that could be used as a starting point for ongoing studies. The logic used for the selection of the base case is described in the next section of the report.

2.2.4 - CAES System Installation

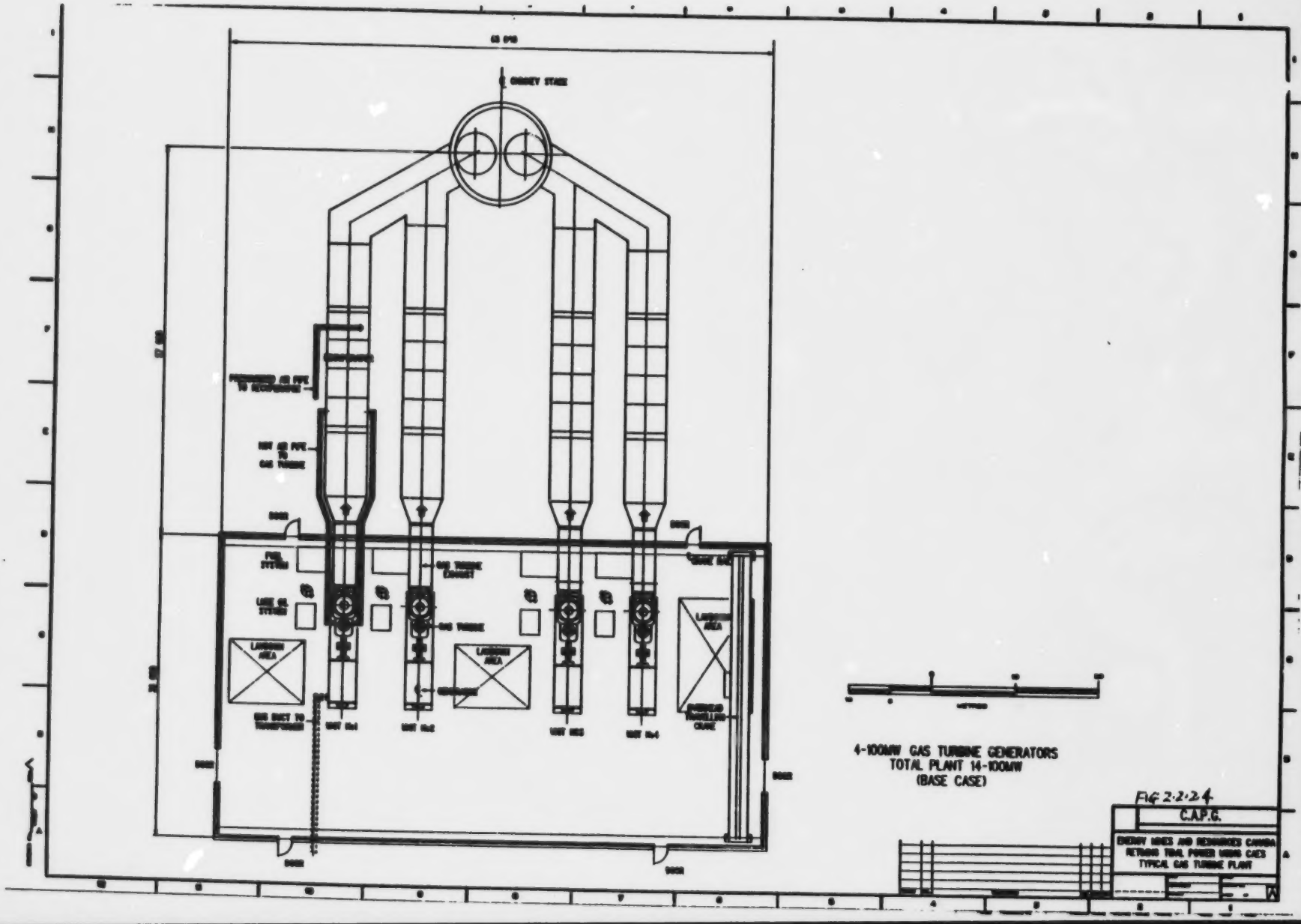
For the base case, the CAES system has been sized to utilize all the available tidal energy during a four-week period. In the following subsections, the analyses carried out to determine the base case storage volume, compressor capacity and gas turbine capacity are described.

2.2.4.1 - Methodology

The analysis has all been carried out using a spreadsheet program (LOTUS 123). Two separate work sheets have been developed which allow for the analysis of a month of tide data and for the analysis of the resultant tidal energy with the CAES system.

To characterize the tidal energy production at Site A8 at the mouth of the Cumberland Basin, four calender months of tide data have been extracted from the Canadian Tide

and Current Tables for the Atlantic Coast in 1982. The specific months chosen were January, April, July and November and are intended to represent not only periods of different tide ranges but also periods when the timing of the tide cycle relative to the solar cycle were different. Tides (1982) were close to average annual tidal conditions.

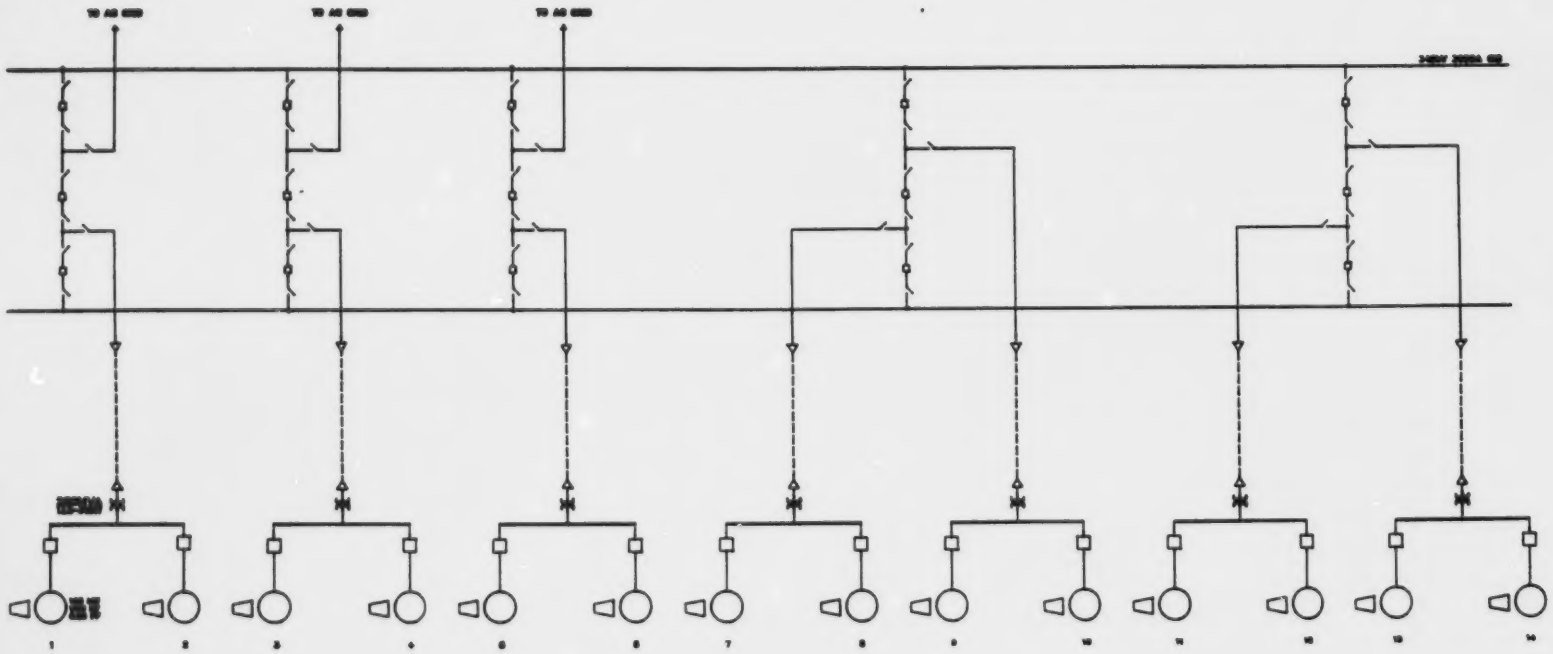


4-100MW GAS TURBINE GENERATORS
TOTAL PLANT 14-100MW
(BASE CASE)

FIG 2.2.24

C.A.P.C.

ENERGY MINES AND RESOURCES CANADA
RETAINED TIDAL POWER MEAN CASES
TYPICAL GAS TURBINE PLANT



BAY OF FUNDY TIDAL POWER
ONE LINE DIAGRAM
GAS TURBINE/GENERATOR

FIG.2.2.2.6

The times and elevations of high and low tide were extracted for Saint John, New Brunswick and adjusted in accordance with the procedure recommended in the Tide Tables to estimate the tide at Peck's Point. The resultant tide ranges were further adjusted for the expected impact of the tidal barrage. Following the 1984 Alcan study, a mean reduction in tidal range at the barrage of 0.64 m (2.1 ft) was applied.

Estimates for the energy produced at the Site A8 tidal power plant were taken from the analyses made for the 1984 Alcan study. Seven sample tides which encompass the full range of tides expected at the site were analyzed during the study. The energy that would be generated during each tide was distributed over time so that a chronological sequence of tidal energy was available for use in the second work sheet where the interaction with the CAES system was investigated. The tidal energy was estimated for each hour and the timing was keyed to the hour of the high tide.

Energy production estimates are based on calculations done in 1984 for the A8 site, computer run reference RES42CVF, 84-10-22.18:25. The equipment characteristics are as follows

- 39 turbines (plus 3 allowed for maintenance)
- rated power 34 MW
- runner size 7.5 m diameter
- fixed runner blades, 14 deg setting
- variable distributor
- variable speed
- draft tube exit area 162 m^2
- unit spacing 19.5 m
- 17 sluice gates

- effective sluice area 311 m^2
- sluice spacing 19.8 m.
- generator efficiency .95

The energy production is based on a single basin scheme with generation on the ebb tide. The following table summarizes the hourly energy yield from seven representative tidal ranges.

Energy Generation, MW hr

Hours from Start of Ebb Tide

Tidal Range	3	4	5	6	7	8	9	Total
7.25		430	717	785	647	344	20	2943
8.25		553	867	956	805	442	52	3675
9.25		643	1031	1125	986	577	99	4461
10.25		806	1173	1271	1142	714	157	5263
10.75		789	1252	1335	1231	800	193	5600
11.75	156	1032	1297	1326	1304	902	233	6248
12.75	429	1086	1318	1321	1323	1014	287	6778

In the second work sheet, the energy which could be delivered to the electric supply system through the Tidal-CAES system was determined. Two separate calculations were made, one in which all the energy is fed through the CAES and the second where tidal energy could be supplied directly if its timing was appropriate. The numberof days per week and the number of hours per day that the energy was to be supplied to the electric system were made variable. The primary output of this second work sheet was the power and energy which could be delivered, the volume of storage required and the natural gas input requirements.

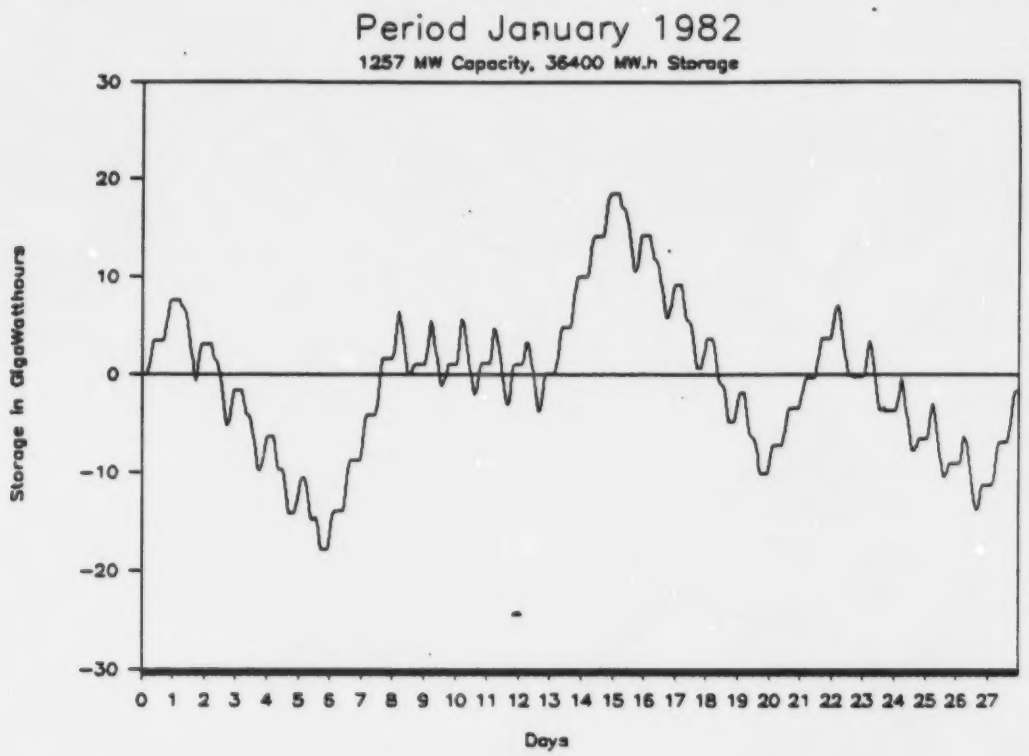
2.2.4.2 - **Findings**

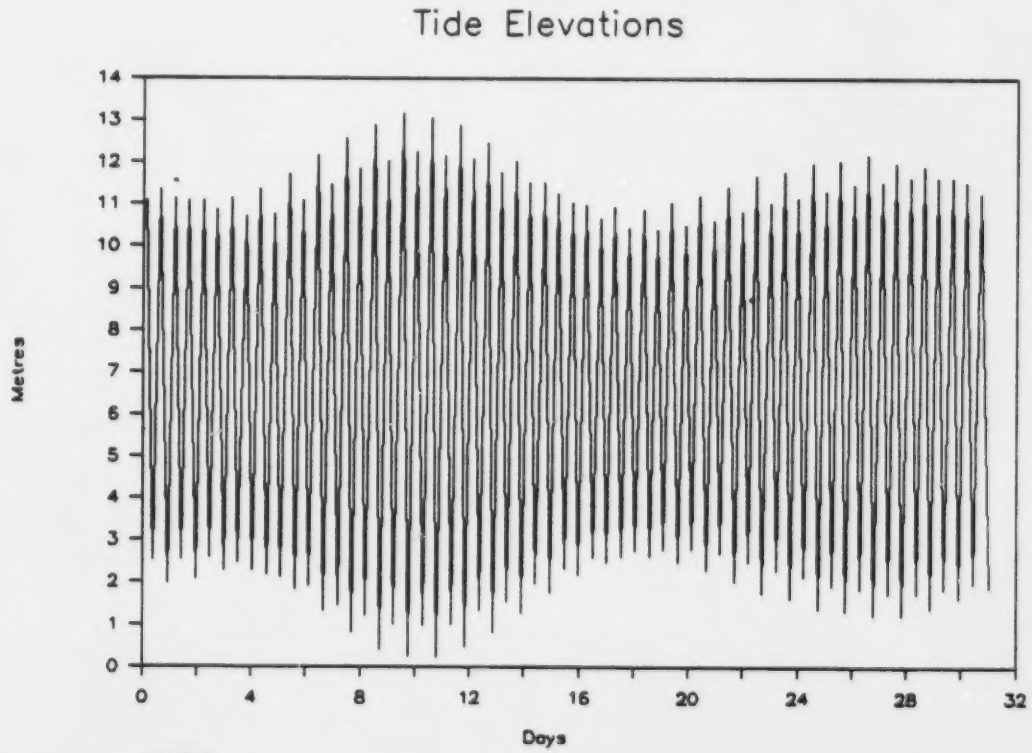
Sample Tidal Cycles

As noted in Section 2.2.3.1, the ranges of the tides at Peck's Point were adjusted to reflect the impact of the tidal barrage. The table below presents some statistics for each of the sample periods.

	Maximum Range (m)	Minimum Range (m)	Energy MWh	Relationship to Average (%)
January	12.10	7.14	260325	-12.12
April	11.52	5.99	255668	-13.70
July	11.75	7.39	257481	-13.08
November	11.23	6.23	252369	-14.81
Average (January adjusted)	13.23	7.81	297915	+0.56
Average based on Annual Histogram			296242	

All of the foregoing samples contain 60 tides. The average based on the annual histogram is 60/705 of the estimated annual energy production. It was found that the characteristics of the histogram of the 60 January tides most closely approximated the annual histogram so that the tide ranges for this month were adjusted to approximate a long term average. Figures 2.2.4.1 through 2.2.4.4 illustrate the sample tides used.





NOTE
Tidal elevations are given for Peck's Point, before adding a correction for the tidal barrage.

Fig. 2.2.4.1

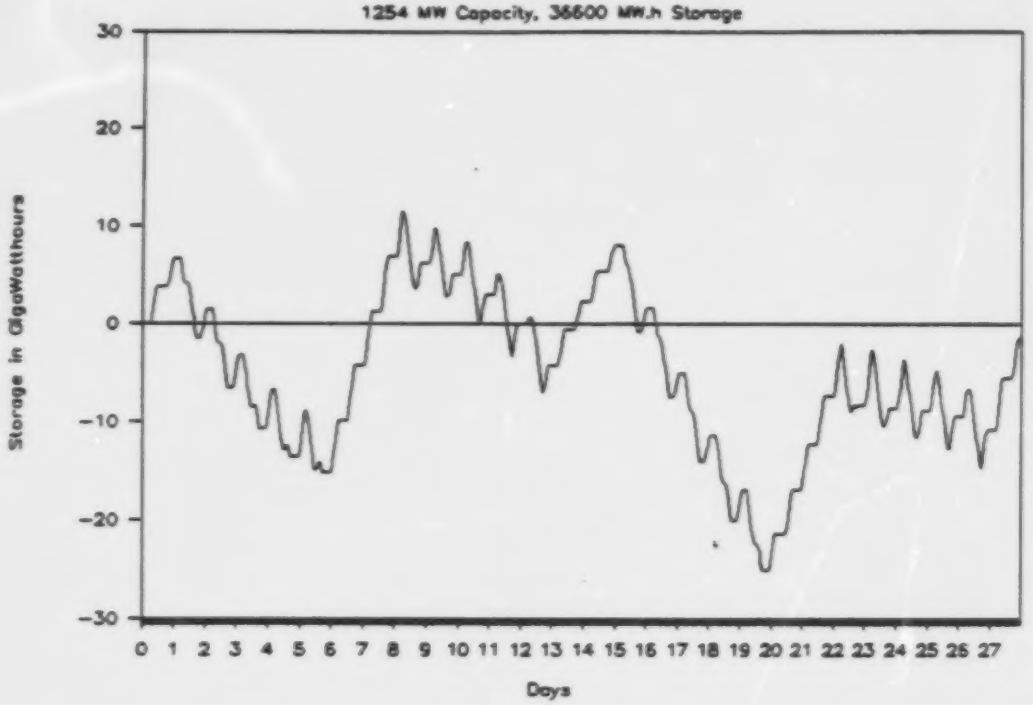
CANADIAN ATLANTIC POWER GROUP LTD
ENERGY MINES AND RESOURCES CANADA
RETIMING TIDAL POWER USING CAES

STORAGE UTILIZATION AND TIDAL RANGE - JANUARY 1982

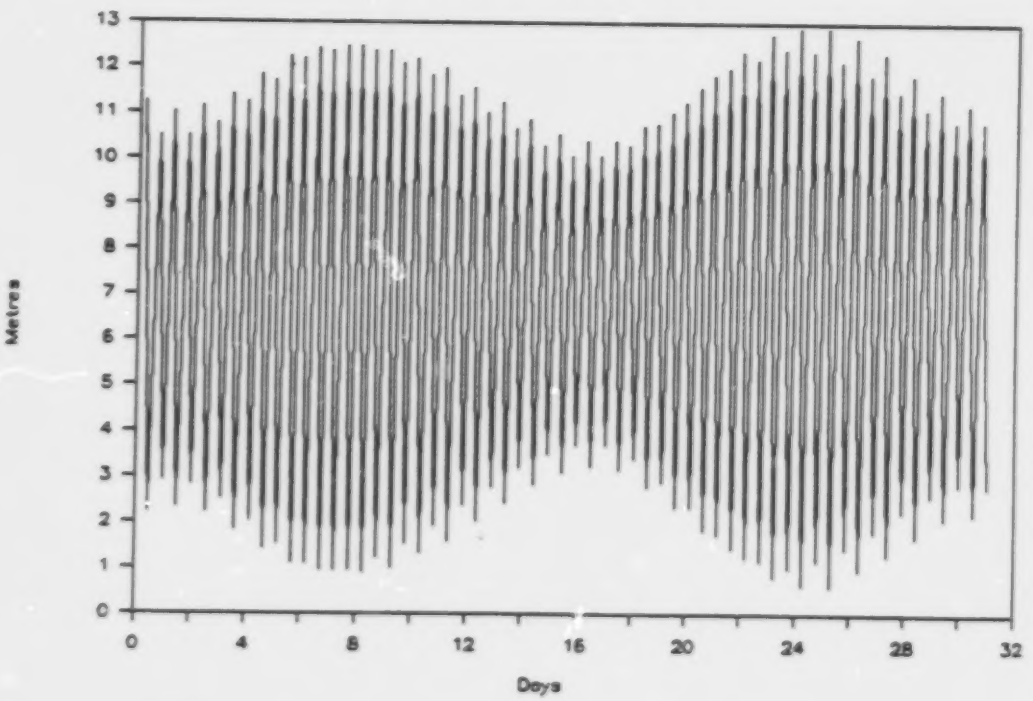
CAPG

Period April 1982

1254 MW Capacity, 36600 MW.h Storage



Tide Elevations



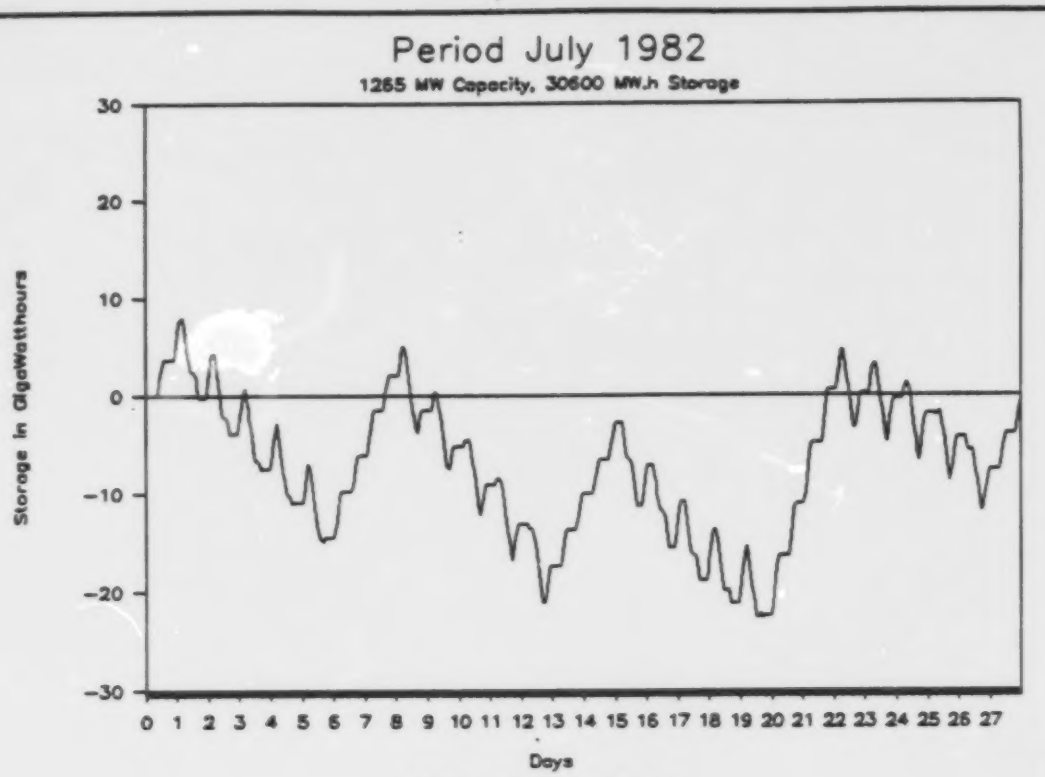
NOTE
Tidal elevations are given for Peck's Point, before adding a correction for the tidal barrage.

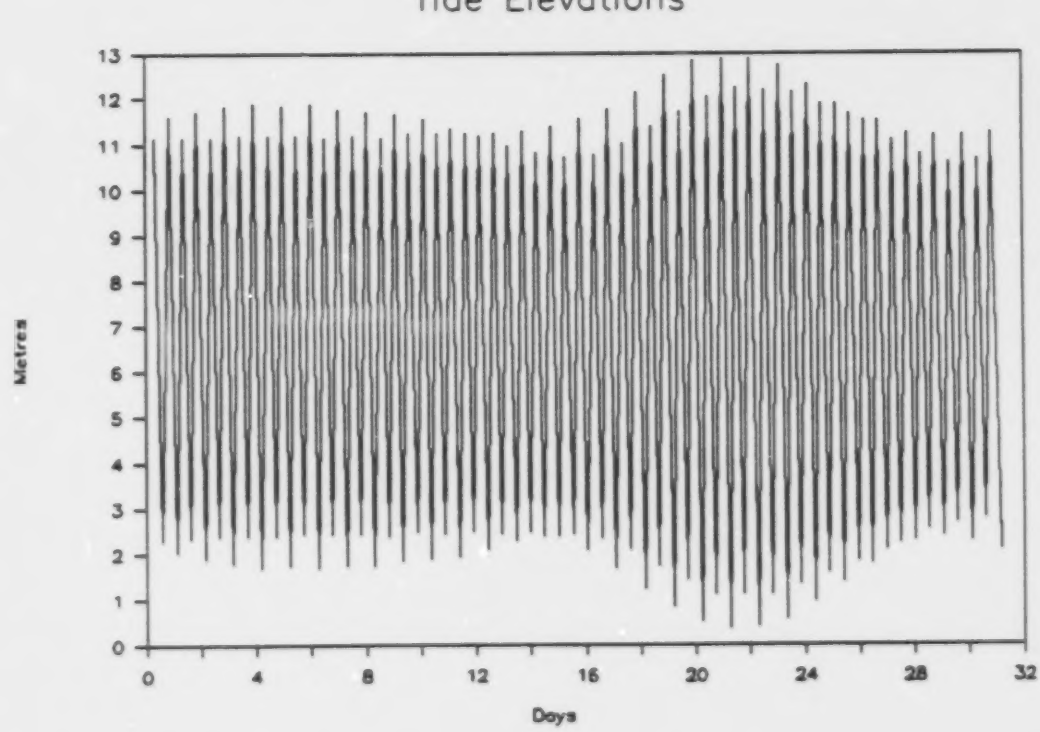
Fig.2.2.4.2

CANADIAN ATLANTIC POWER GROUP LTD
ENERGY MINES AND RESOURCES CANADA
RETIMING TIDAL POWER USING CAES

STORAGE UTILIZATION AND TIDAL RANGE - APRIL 1982

CAPG





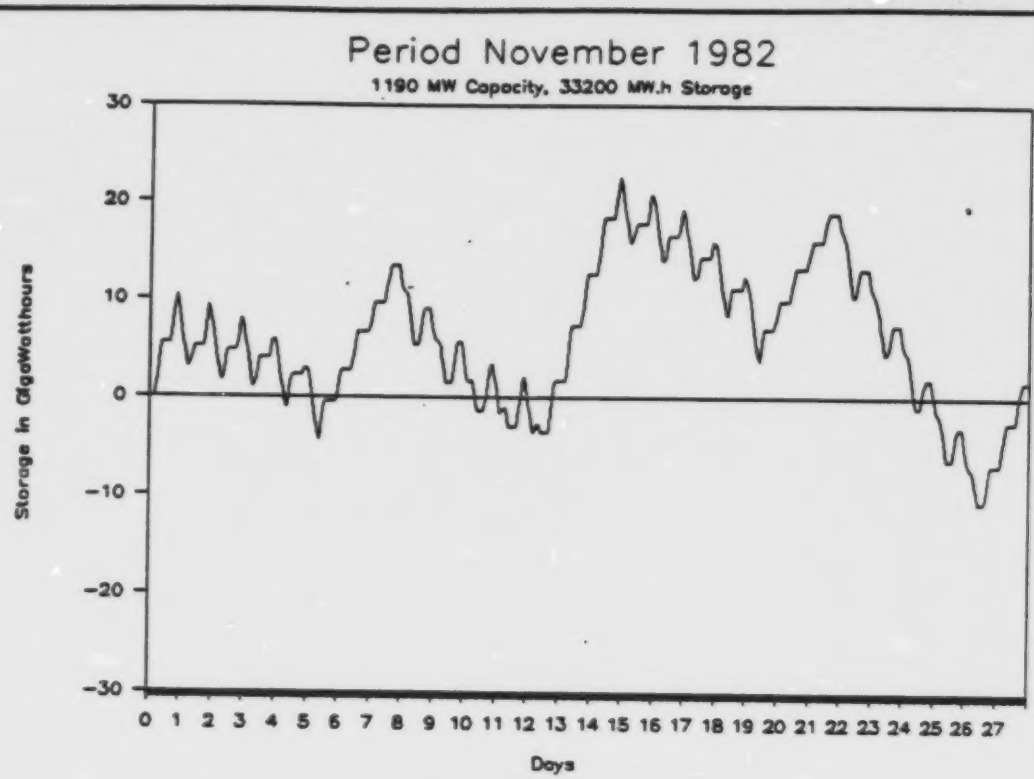
NOTE
Tidal elevations are given for Peck's Point, before adding a correction for the tidal barrage.

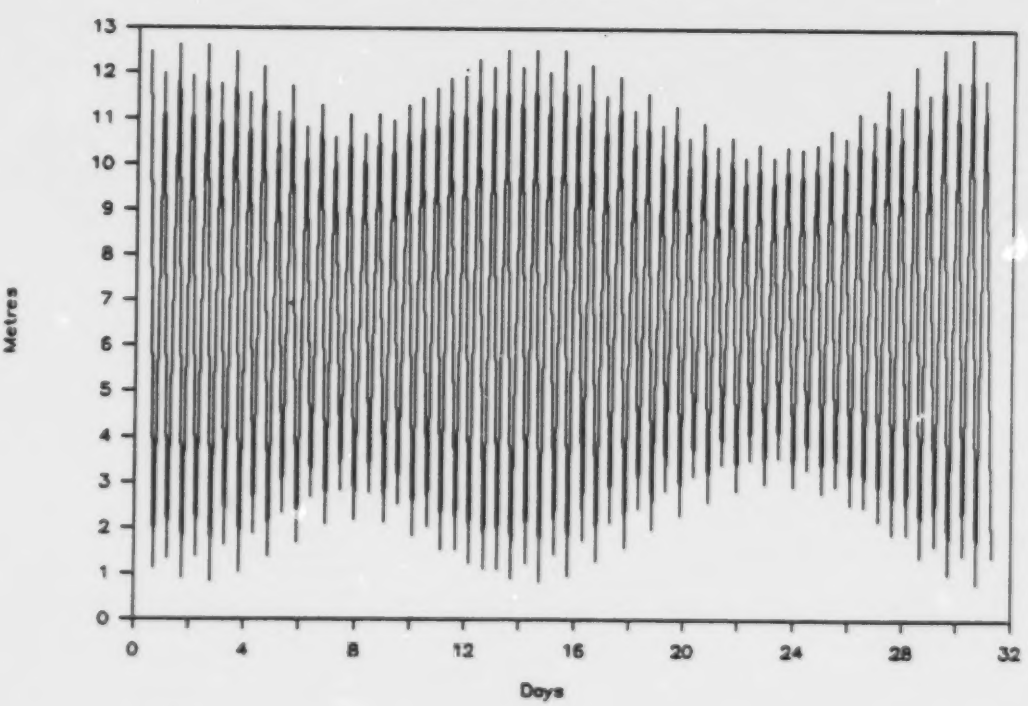
Fig. 2.2.4.3

CANADIAN ATLANTIC POWER GROUP LTD
ENERGY MINES AND RESOURCES CANADA
RETIMING TIDAL POWER USING CAES

STORAGE UTILIZATION AND TIDAL RANGE - JULY 1982

CAPG





NOTE
Tidal elevations are given for Peck's Point, before adding a correction for the tidal barrage.

Fig.2.2.4.4

CANADIAN ATLANTIC POWER GROUP LTD
ENERGY MINES AND RESOURCES CANADA
RETIMING TIDAL POWER USING CAES

STORAGE UTILIZATION AND TIDAL RANGE - NOVEMBER 1982

CAPG

Tidal Energy and CAES Analysis

As an initial set of assumptions, the electric system was assumed to require a fixed amount of power for 12 hours per day, 5 days per week. Given this pattern of demand, it was decided to analyze a 28-day period as this represents a whole number of weeks as well as being approximately one lunar cycle.

To determine the amount of storage required to retime the tidal energy, it was assumed that the initial and final storage volumes should be equal. The state of the storage at the beginning of the analysis has no major significance other than the fact that some initial charging will be required and will represent an additional "capital cost" to the system. The difference between the maximum and minimum storage during the period of analysis was taken as the minimum storage required to fully utilize the tidal energy during the period.

The formula relating input to output requirements of the high pressure gas turbines is

0.78 kW.h electrical energy input)
plus) = 1 kW.h retimed
1.17 kW.h (1.17x3600 kJ) fuel) electrical energy

This could be compared to a conventional energy storage plant that stores 1 kW.h and returns it at 75% overall efficiency, and a thermal plant with a 45% thermal efficiency (8000 kJ/kW.h). If the storage plant retimed 1 kW.h and the thermal plant converted 1.17x3600 kJ of fuel, they would deliver 1x75+1.17x.45 = 1.28 kW.h. The mean efficiency of the combined systems is 51%.

The following tables summarize the principal findings of the Tidal-CAES system studies.

TABLE 2.2.4.1

ALL TIDAL ENERGY
ROUTED TO STORAGE

Tide Sample

	Power Available (MW)	Tidal Input (GWh)	Storage Required (GWh)
January	1257	235.45	36.4
April	1254	235.09	36.6
July	1265	238.07	30.6
November	1190	224.06	33.2
Average	1430	267.63	39.6
(Jan)			

TABLE 2.2.4.2

SOME TIDAL ENERGY
SUPPLIED DIRECT TO SYSTEM

Tide Sample

	Power Available (MW)	Tidal Input (GWh)	Storage Required (GWh)
January	1150	235.45	35.9
April	1151	235.09	34.8
July	1165	238.07	29.1
November	990	224.06	28.6
Average	1305	267.63	38.8
(Jan)			

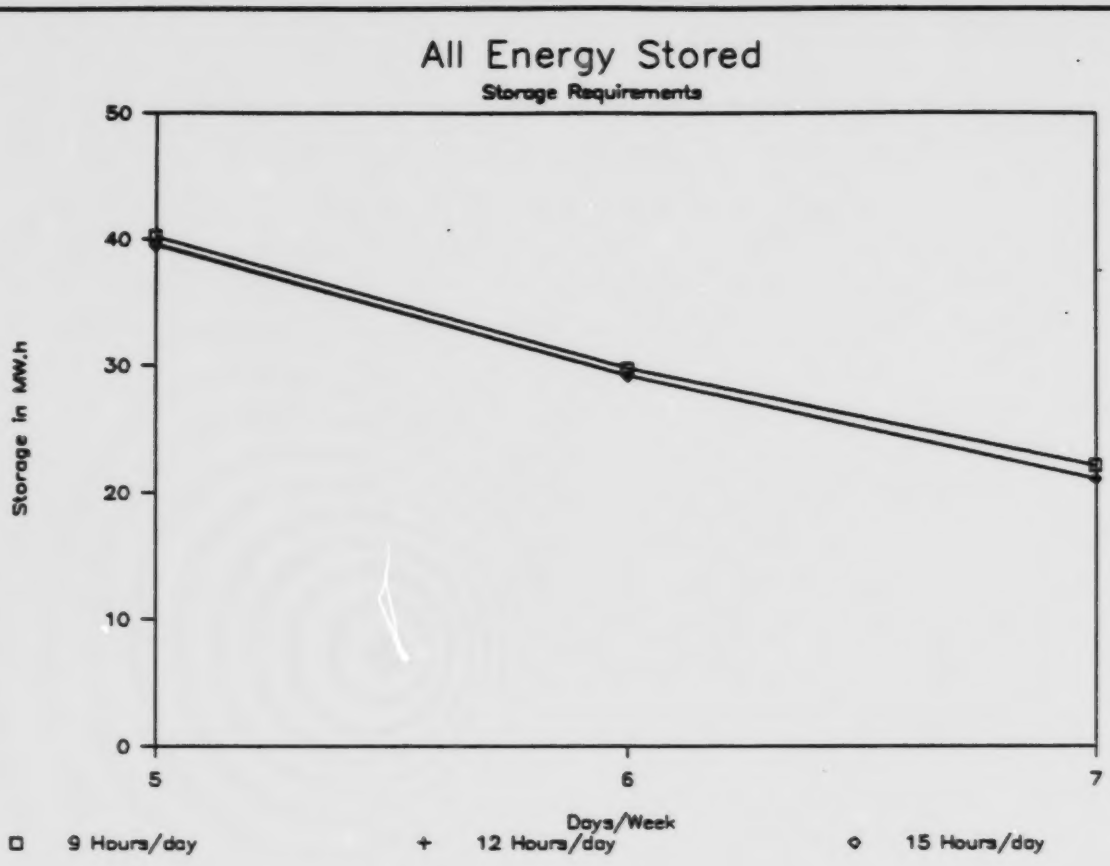
It is apparent from Tables 2.2.4.1 and 2.2.4.2 that the volume of storage required by each system is virtually identical. If the storage required to retime the average tide is taken as indicative of the maximum, 40 GWh of storage would be required for a tidal plant at site A8.

The pattern of storage use is shown in Figures 2.2.4.1 to 2.2.4.4.

If the number of days of supply is increased, the volume of the storage requiredis decreased. This is shown in Figures 2.2.4.5 and 2.2.4.6. If the number of days of supply is increased from 5 to 6 then the storage required is reduced by about 25%. Whether in fact one would limit the storage based upon a predefined mode of operation is questionable as the availability of excess storage capacity would add appreciably to the overall operating flexibility of the Tidal-CAES system.

The effect of varying the load profile on the capacity of the compressed air turbine generators is shown in Figures 2.2.4.7 and 2.2.4.8.

Within the Terms of Reference for this study, it has not been possible to investigate the potential for storage use over a longer period than one month. As may be seen in Tables 4.1.1 and 4.1.2, there is some variability from month to month. If the output from the synthetic average tide cycle is indicative, the monthly variation could be as much as 19%. The potential to reduce this variation through the use of longer term storage requires considerable additional work using several consecutive months of tide cycles.



The basic load profile used for previous sensitivity tests has used a 5 days/week 12 hours/day load profile.

The figure shows how the storage requirements change as the load profile varies. Refer to Section 2 for the absolute cavern volume as determined by storage requirements.

Storage requirements are related to energy supplied from the tidal plant (i.e., to the gas compressors).

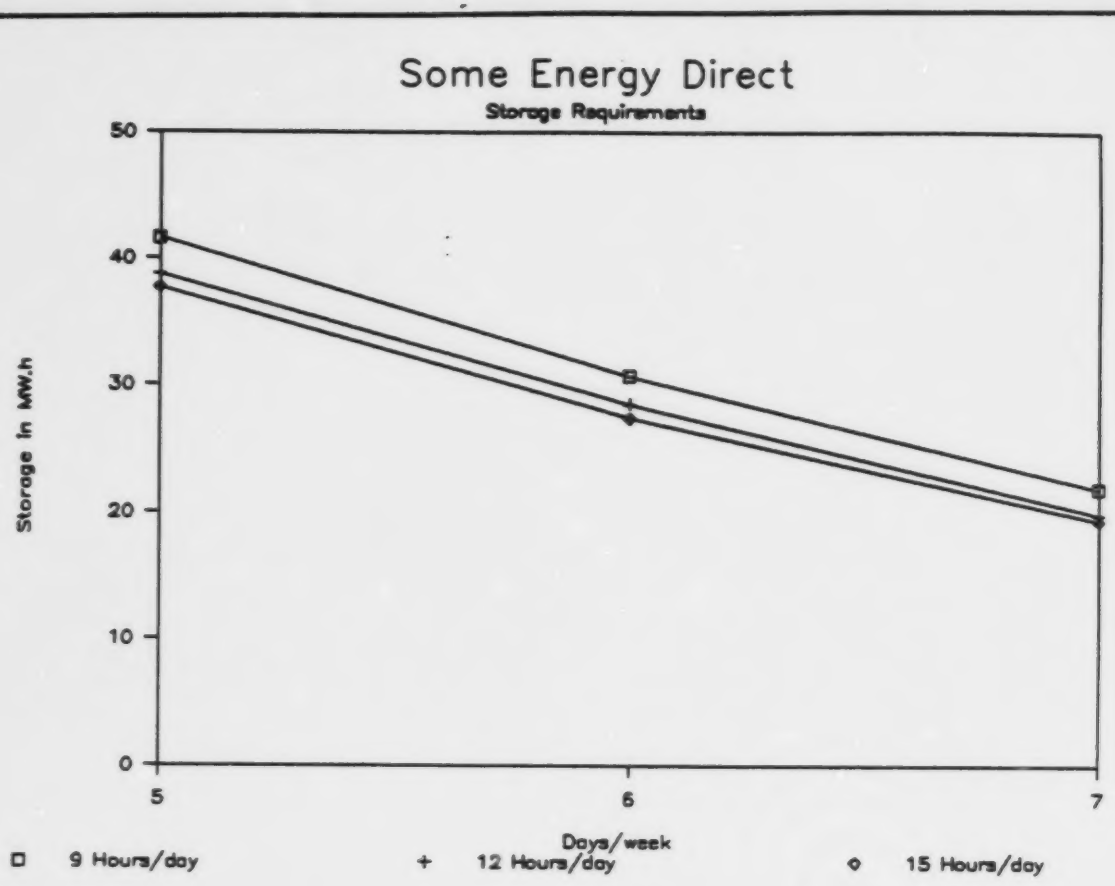
The figure is calculated for the case where all energy is routed through storage.

Fig. 2.2.4.5

CANADIAN ATLANTIC POWER GROUP LTD
ENERGY MINES AND RESOURCES CANADA
RETIMING TIDAL POWER USING CAES

CAPG

STORAGE AT CAES PLANT,
SENSITIVITY TO LOAD PROFILE, ALL ENERGY ROUTED THROUGH STORAGE



The basic load profile used for previous sensitivity tests has used a 5 days/week, 12 hours/day load profile.

The figure shows how the storage requirements change as the load profile varies. Refer to Section 2 for the absolute cavern volume as determined by storage requirements.

Storage requirements are related to energy supplied from the tidal plant (i.e., to the gas compressors).

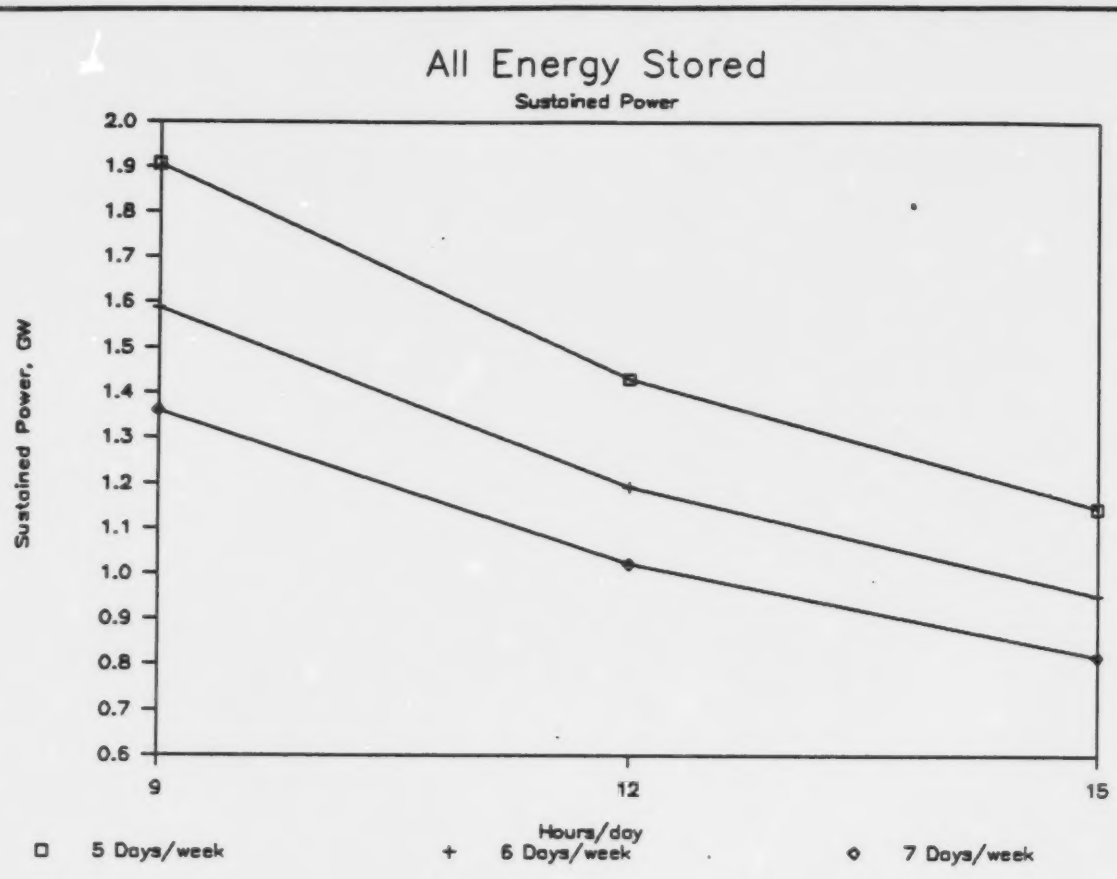
The figure is calculated for the case where energy is supplied direct to market when supply and demand are coincident.

Fig. 2.2.4.6

STORAGE AT
CAES PLANT , SENSITIVITY
TO LOAD PROFILE, SOME TIDAL ENERGY ROUTED DIRECT TO MARKET

CANADIAN ATLANTIC POWER GROUP LTD
ENERGY MINES AND RESOURCES CANADA
RETIMING TIDAL POWER USING CAES

CAPG



The basic load profile used for previous sensitivity tests has used a 5 days/week 12 hours/day load profile.

The figure shows how much capacity should be installed in the final expansion turbines and generators of the Compressed Air Energy Storage plant as the load profile is varied.

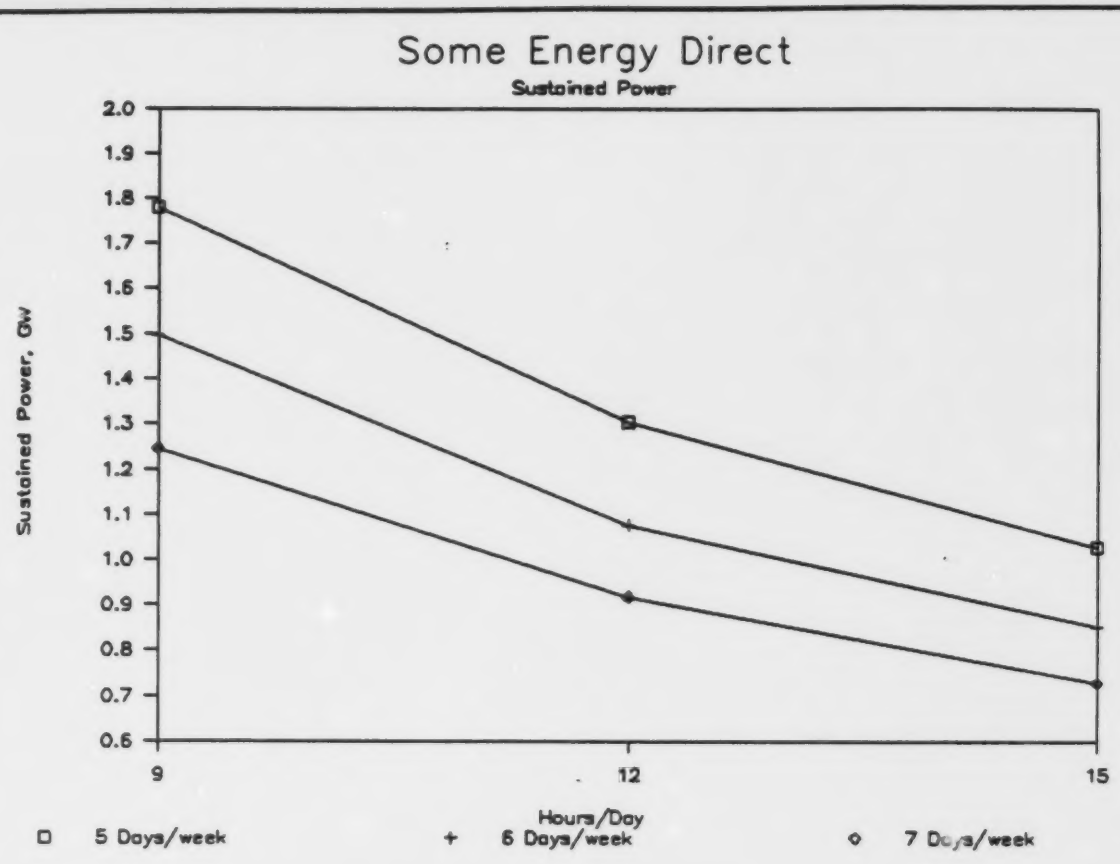
The figure is calculated for the case where all energy is routed through storage.

Fig. 2.2.4.7

CANADIAN ATLANTIC POWER GROUP LTD
ENERGY MINES AND RESOURCES CANADA
RETIMING TIDAL POWER USING CAES

CAPACITY AT CAES GENERATION PLANT,
SENSITIVITY TO LOAD PROFILE, ALL ENERGY ROUTED THROUGH STORAGE

CAPG



The basic load profile used for previous sensitivity tests has used a 5 days/week, 12 hours/day load profile.

The figure shows how much capacity should be installed in the final expansion turbines and generators of the Compressed Air Energy Storage plant as the load profile is varied.

The figure is calculated for the case where energy is supplied direct to market when supply and demand are coincident.

Fig. 2.2.4.8

CAPACITY AT CAES GENERATION PLANT, SENSITIVITY TO LOAD PROFILE, SOME TIDAL ENERGY ROUTED DIRECT TO MARKET

CANADIAN ATLANTIC POWER GROUP LTD
ENERGY MINES AND RESOURCES CANADA
RETIMING TIDAL POWER USING CAES

CAPG

2.2.4.3 - Cavern Storage Requirements

The cavern size required to store the calculated amounts of energy depends on the following factors.

(a) Compensated or uncompensated storage.

(b) Storage pressure or pressure range.

(c) Air temperature.

The water compensated constant pressure storage volume is typically less than the fixed volume/variable pressure storage uncompensated storage. The assumptions used in the following table of storage volumes are considered reasonable and provide a theoretical value for the storage required without allowance for losses due to leakage or changes in cavern size.

CAES TIDAL POWER - STORAGE VOLUME

	Volume Requirements ($m^3 \times 10^6$)	
Tidal Period	Compensated	Uncompensated
January 1982	5.02	10.19
April 1982	5.05	10.24
July 1982	4.22	8.57
November 1982	4.58	9.29
Average	5.47	11.09

Volume requirements are based on

(a) A8 site, 39 turbines of 34 MW each

(b) Energy is delivered on five 12 hr days per week, in accordance with firm capacity data given above

(c) All energy is routed through storage

(d) For one unit of marketed energy, 0.78 units of energy from tidal power is used for air compression

(e) The compensated cavern volume is operated at 42 bar

(f) The uncompensated cavern is operated over a pressure range of 46 bar to 66 bar.

(g) A volume of 280 m^3/(input MW.h) is required for the uncompensated cavern volume at the above pressure range.

The calculated volumes show that the compensated volume requirement is substantially less than the uncompensated volume, even though a lower pressure has been assumed for the compensated storage.

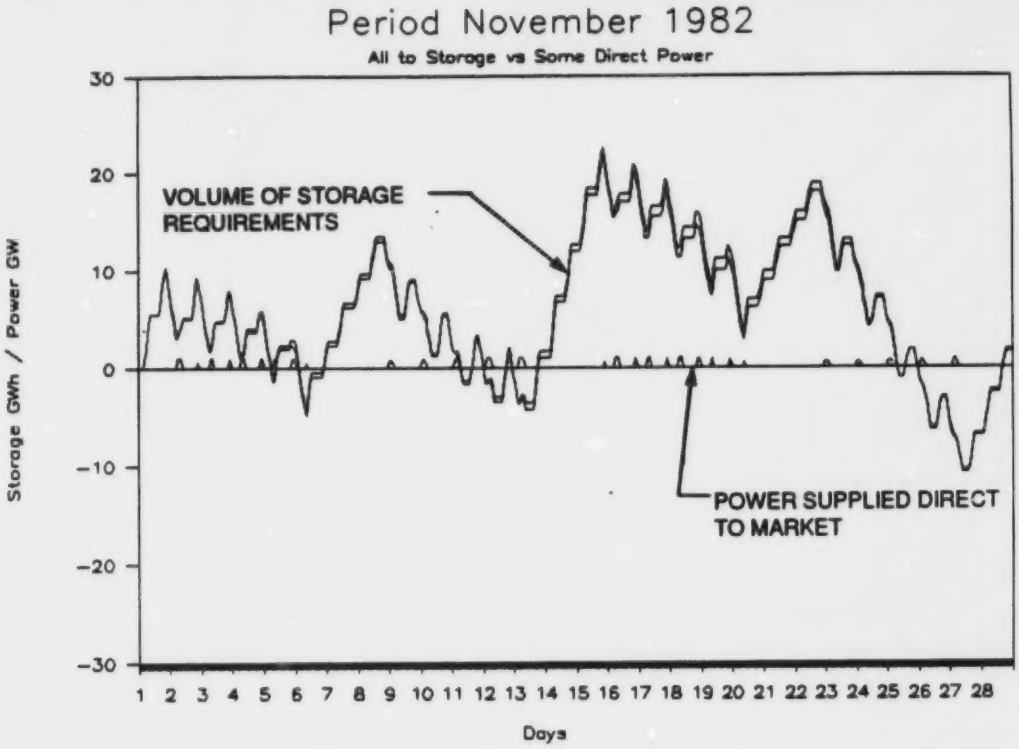
The pressure range assumed for the uncompensated storage is the same as that used in the Huntorf air storage plant. However, the Huntorf plant is claimed to have an input energy storage capacity of 59 MW for 8 hours using 283 000 m^3 of cavern volume. This amounts to 600 m^3/(input MW h). This is substantially greater than

the theoretical minimum volume required with the stated pressure range capability of the plant, that is

280 m^3/(input MW.h).

For the base case estimate it has been assumed that a similar proportionate increase in theoretical storage volume to that at Huntorf would be required. However, the storage volume at Huntorf is created by two solution mined caverns separated by 500 ft. It is assumed that the design has a built-in redundancy to allow continued operations at rated output if there are problems with one of the caverns. The much larger storage volume required for the tidal power CAES plant would probably be constructed with more than two solution-mined caverns. In this event, less redundant storage would be required.

The option of sending some of the electrical energy direct to market is evaluated in a later section. This has only a secondary effect on storage, as indicated in Figure 2.2.4.9.


Period November 1982
All to Storage vs Some Direct Power
Storage GWh / Power GW
30
20
10
0
−10
−20
−30
VOLUME OF STORAGE REQUIREMENTS
POWER SUPPLIED DIRECT TO MARKET
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28
Days

This figure compares storage requirements for

- a system that routes all energy through storage
- a system that sends power direct to market when supply and demand are coinsident.

The figure clearly shows that the volume of storage required is not affected significantly by these options.

Fig. 2.2.4.9

CANADIAN ATLANTIC POWER GROUP LTD
ENERGY MINES AND RESOURCES CANADA
RETIMING TIDAL POWER USING CAES

DIRECT SALE OF TIDAL POWER - EFFECT ON STORAGE

CAPG

2.2.5 - Cost Estimates

The cost estimate summarized in Table 2.2.5.1 was prepared for the base case installation consisting of a separate tidal power generating station and separate compressor and gas turbine plants. Details of the components of the estimate are given in Tables 2.2.5.2 to 2.2.5.5 inclusive. The estimate assumes that air storage is in solution mined caverns in nearby salt deposits. In Tables 2.2.5.6 and 2.2.5.7 comparative estimates are given for storage in caverns in hard rock at the Cobequid Mountain area and in less competent rock at Site A8. Descriptions of the geology for each storage site are given in a later section of the report.

TABLE 2.2.5.1

RETIMING TIDAL POWER USING CAES

Base Case - Summary Estimate of Cost

Item No.	Description	Total $CDN 1987 Millions
1	Tidal Power Plant + Transmission 42 turbine generators at 34 MW each	2,918.4
2	Compressor Plant 24-60 MW compressors	738.8
3	Gas Turbine Generator Plant 14-100 MW gas turbines	573.8
4	Air Storage Facility 20.1 million m^3	130.0
	TOTAL	4,361.0

TABLE 2.2.5.2

ESTIMATE FOR CAES TIDAL POWER FACILITY
(1984 Recommended Scheme - Alcan)

Facility Description:

Installed Capacity 1 428 MW - 42 Turbine Generators 34 MW each and 20 Sluiceways.

Location: Straight line between Peck's Point, New Brunswick and Boss Point, Nova Scotia.

ESTIMATE

Escalated estimate from Alcan Report on Fundy Tidal Power Stage I - Recommended Scheme (Jan 1984)

Item No.	Description	$Can x 10^6 January 1984	$Can x 10^6 December 1987
I	Power Plant		
	A. Side installations, docks, wharves	139	158.5
	B. Dikes	18	20.5
	C. Dredging, mattress	175	199.5
	E. 1. Civil	215	245.1
	2. Mechanical	66	75.2
	3. Electrical	included	included
	4. Turbine-generators	531	605.3
	F. Sluice caissons, cribs	249	283.9
	G. Under water rock excavation	17	19.4
	H. Miscellaneous	6	6.8
	I. Power plant, direct costs	1,416	1,614.2
	J. Infrastructure cost	102	116.3
II	Transmission Line & Substations		
	K. Transmission line	412	469.7
	L. Control building	5	5.7
	M. Cables to shore	2	2.3
	N. Rectifier	44	50.2
	O. Inverter	36	41.0
	P. Miscellaneous	41	46.7
	Q. Transmission, direct + ind. cost	540	615.6

III	**Management & Owner's Contingency**			
	R. Project management services (I + Q) x 10%		195	222.3
	S. Owner's expense (I + Q) x 3%		59	67.3
	T. Owner's contingency			
	(A + B + C + E1 + F + G + H)	x 15%	123	140.2
	(E2 + N + O)	x 8%	12	13.7
	(E4	x 6%	32	36.5
	(J + K + L + M + P + R + S)	x 10%	81	92.3
	TOTAL		502	572.3
IV	**Summary**			
	U. Total		2,560	2,918.4

TABLE 2.2.5.3

ESTIMATE FOR CAES COMPRESSOR PLANT

Facility Description:

24-60 MW Compressors housed in four separate buildings containg 6 units each.

Location: Adjacent to the air storage facility.

Surface Area: 450 M by 250 M

Building Area: 5500 m^2 by 4

ESTIMATE

Item No.	Description	Unit	Quantity	Unit Cost	Total $Can 1987
1	Site Preparation	HA	15	10,000	150,000
2	Site Access Roads	Km	2	150,000	300,000
3	Temporary Facilities	-	-	Lump sum	20,000,000
4	Buildings	m^2	22,000	1,100	24,200,000
5	Permanent Equipment	Each	24	11,600,000	278,400,000
6	Installation of permanent equipment	-	-	Lump sum	56,000,000
7	Electrical and mechanical services, supply and install	-	-	Lump sum	97,440,000
8[1]	Substations	-	-	Lump sum	177,900,000
9	345 kV-double circuit transmission line 3 nos by 8 km/line	km	24	350,000	8,400,000
10	Engineering and management	-	-	Lump sum	28,000,000
11	Owner Cost	-	-	Lump sum	13,000,000
12	Contingency	-	-	Lump sum	35,000,000
	TOTAL				738,790,000

[1]Includes substations required at Tidal Power Plant and CAES plant plus rectifier/inverter.

*Includes substations required at Tidal Power Plant and CAES plant plus rectifier/inverter.

TABLE 2.2.5.4

ESTIMATE FOR CAES GAS TURBINE GENERATOR PLANT

Facility Description:

14-100 MW Gas-Turbine Generators housed in two separate buildings.

Location: Adjacent to the air storage facility.

Surface Area: 150 M by 150 M

Building Area: 4158 m^2 by 2

ESTIMATE

Item No.	Description	Unit	Quantity	Unit Cost	Total $Can 1987
1	Site Preparation	HA	5	10,000	50,000
2	Site Access Roads	km	1	150,000	150,000
3	Temporary Facilities	-	-	Lump sum	20,000,000
4	Buildings	m^2	8,316	1,100	9,200,000
5	Permanent Equipment	Each	14	18,500,000	259,000,000
6	Installation of Permanent Equipment	-	-	Lump sum	52,000,000
7	Electrical plus mechanical services, supply and install	-	-	Lump sum	103,600,000
8	Substation	-	-	Lump sum	68,800,000
9	Engineering and Management	-	-	Lump sum	26,000,000
10	Owner Cost	-	-	Lump sum	12,000,000
11	Contingency	-	-	Lump sum	29,000,000
	TOTAL				573,800,000

TABLE 2.2.5.5

ESTIMATE FOR CAES - STORAGE CAVERN IN SALT DOME

Location: Northeast of Boss Point (by 7.6 km) between the east shore of Cumberland Basin and the Herbert River embayment. Boss Point is the east abutment of the dam for the A8 tidal power scheme.

Facility Description:

A. Underground Storage

Surface Area: 3000 m by 3000 m

Cavern Dimensions: 13 cylindrical vertical caverns required 300 m high by 62 m in diameter each.

Cavern Volume: 13 million m^3

Work Access: Steel well casing shafts 50 cm to 18 cm by 600 m deep

B. Suface Reservoir - Not required

ESTIMATE

Quantity	Unit Price	Total
13,000,000 m^3	\$10.00/m^3	\$130,000,000[1]

[1]The price includes the cost of the well, leaching, brine disposal and well headers. Also included are management, owner's costs and contingency allowance.

TABLE 2.2.5.6

ESTIMATE FOR CAES - STORAGE CAVERN IN HARD ROCK

Location: 2 km southeast of east Mapleton (32 km southeast of the A8 tidal power scheme).

Facility Description:

A. Underground Storage

Surface Area: 2000 m by 1200 m

Cavern Dimensions: 34 parallel caverns 20 m wide by 30 m high by 300 m long with a tunnel 10 m wide by 8 m high across one end.

Cavern Volume: 6 million m^3

Work Access: 10 shafts, 7 m diameter by 600 m deep

B. Surface Reservoir: 870 m diameter by 12 m high

ESTIMATE

Item No.	Description	Unit	Quantity	Unit Cost	Total $Can 1987
1	Site Preparation	HA	200	10,000	2,000,000
2	Site Access Roads	km	5	150,000	750,000
3	Temporary Facilities	-	-	Lump sum	90,000,000
4	Shaft Excavation				
	- Sinking	m^3	24,000	700	16,800,000
	- Raising	m^3	240,000	600	144,000,000
	- W.W.M.	m^2	150,000	20	3,000,000
	- 3 m Rock Bolts	Nos	50,000	225	11,250,000
	- 100 mm shotcrete	m^2	-	Lump sum	5,000,000
5	Tunnel Excavation				
	- Drill and Blast	m^3	6,000,000	50	300,000,000
	- 5 m Rock Bolts	Nos	40,000	300	12,000,000
	- W.W.M.	m^2	350,000	15	5,250,000
	- 100 mm Shotcrete	m^2	30,000	90	2,700,000
6	Reservoir				
	- Earth fill dam	m^3	1,000,000	20	20,000,000

7	Miscellaneous	-	-	Lump sum	20,000,000
8	Engineering and Management	-	-	Lump sum	55,000,000
9	Owner Cost	-	-	-	15,000,000
10	Contingency	-	-	-	107,000,000
	TOTAL				809,750,000

TABLE 2.2.5.7

ESTIMATE FOR CAES - STORAGE CAVERN IN SOFT ROCK

Location: East shore of the Cumberland Basin in Nova Scotia at Boss Point close to the east abutment of the A8 tidal power scheme.

Facility Description:

A. Underground Storage

Surface Area: 2000 m by 200 m

Cavern Dimensions: 5 m by 5 m tunnels (39 Nos in both north/south and east/west directions). Total 270 km of tunnel.

Work Access: 10 shaft, 7 m diameter by 600 m deep

B. Surface Reservoir: 870 m diameter by 12 m high.

Earth Fill Dam Volume: 1,000,000 m^3

ESTIMATE

Item No.	Description	Unit	Quantity	Unit Cost	Total $Can 1987
1	Site Preparation	HA	200	10,000	2,000,000
2	Site Access Roads	km	5	150,000	750,000
3	Temporary Facilities	-	-	Lump sum	90,000,000
4	Shaft Excavation				
	- Sinking	m^3	24,000	700	16,800,000
	- Raising	m^3	240,000	600	144,000,000
	- W.W.M.	m^2	150,000	20	3,000,000
	- 3 m Rock Bolts	Nos	37,000	225	8,325,000
	- 100 mm Shotcrete	m^2	150,000	100	15,000,000
5	Tunnel Excavation				
	- Road Header	m^3	6,000,000	60	360,000,000
	- 2.5 m - Rock Bolts	Nos	720,000	150	108,000,000
	- 3.5 m - Rock Bolts	Nos	88,000	210	18,480,000
	- W.W.M.	m^2	630,000	15	9,450,000
	- 100 mm Shotcrete	m^2	630,000	90	56,700,000

6	Reservoir - Earth fill dam	m^3	1,000,000	20	20,000,000
7	Miscellaneous	-	-	Lump sum	20,000,000
8	Engineering and Management	-	-	Lump sum	75,000,000
9	Owner Cost	-	-	-	19,000,000
10	Contingency	-	-	-	185.000.000
	TOTAL				1.151.505.000

2.2.5.1 - **Exclusions**

The estimates do not include the following items.

- Escalation beyond December 31, 1987
- Interest during construction
- Land acquisition and/or right of way costs
- Financial costs.

2.2.5.2 - **Level of Accuracy**

The level of accuracy for the tidal power facility, Site A8, is plus/minus 15%. For the other items the accuracy is considered to be plus/minus 20% due to the level of detail of the study at this first cut exercise of combining CAES with a tidal power facility.

2.2.5.3 - **Basis for Estimates**

(a) Tidal Power Facility
Plus Transmission

The Alcan Aluminium Limited - Fundy Tidal Power Stage I, January 1984 Report provided the cost data for the tidal power facility and transmission facilities feeding into the NEPOOL system at Ludlow, Massachusetts. The estimates given in the report for the recommended scheme were escalated using the Statistics Canada comprehensive index for hydro-electric generating stations. The Statistics Canada data was used for the time interval January 1984 to December 31, 1986 and an allowance of 5% escalation

was used for 1987. The net result is a 14% increase over the January 1984 costs.

(b) Compressor Plant

The permanent equipment costs are estimating prices based on budget quotations from suppliers and these have been compared to available historical pricing data for similar equipment. The selection and sizing of the compressors for the facility took into account the technical features and capacities of units presently available from manufacturers. The installation costs are based on historical percentages of the supply cost.

The costs of the required power transformation and switchgear at the tidal power generating plant and at the compressor plant are included in the estimate under the title "substations." These items include the cost of rectifier/inverter equipment. The change in cost due to use of fixed speed turbine generators and ac transmission to the compressor plant is discussed later in Section 4 of the report.

The industrial building required to house the compressed air facility was priced based on recent costs for similar type of construction.

The overall cost was then checked against historical information for similar installations.

(c) Gas Turbine
Generator Plant

The costs for the gas turbine facility were developed as for the compressor plant. The estimate includes the substation required at the gas turbine plant. The cost of the outgoing rectifier equipment and inverter equipment at Ludlow, Mass., are covered in the estimate for the tidal power plant.

(d) Compressed Air
Storage Cavern(s)

The cost for air storage in rock caverns is based on historical costs for similar structures in Canada. Tunneling and shaft costs were checked and modified to account for the magnitude of the work.

The cost of the air storage facility developed by solution mining in a salt dome deposit is based on historical cost information that has been adjusted to cover the magnitude of capacity required and the site location.

2.2.5.4 - Construction Schedule

The construction schedule for CAES with tidal power is presented in Figure 2.2.5.1. The construction schedule has an overall duration of 93 months with the first commercial power being available at month 84. The CAES is designed and installed and commissioned to match the

on line dates for commercial power from the tidal power plant as given in the Alcan 1984 report for Site A8.

The schedule for the CAES is based on the supply of standard equipment for the compressed air and gas turbine facilities. If permanent equipment outside of the present state of the art is required, then the schedule for these facilities would commence on the designated day 1 of the schedule rather than month 6 for the compressed air facility and month 12 for the gas turbine facility. In addition, the actual fabrication of the units would probably end up on an accelerated schedule due to the longer lead time required for design and model testing of the units.

The duration for the design tendering and construction of the compressed air storage facility is based on having 4 wells under construction at the same time. This is considered to be a reasonable number of wells to have under construction at one time in order to reduce the mobilization/demobilization costs of the well drilling rigs and the power demand for brine pumping. The average time duration for a cavity to be created is 15 months.

Using standard equipment for the compressed air and gas turbine facilities allows a delay in commencing those activities and in turn results in less demand on the cash flow in the early years of the construction program. In addition, the transmission system has ample float and is therefore shown to commence later in the construction schedule to allow cash flow leveling.

The schedule includes time for design, tendering, approvals and weather delays and, as such, presents a reasonable time frame to construct a project of such a magnitude.

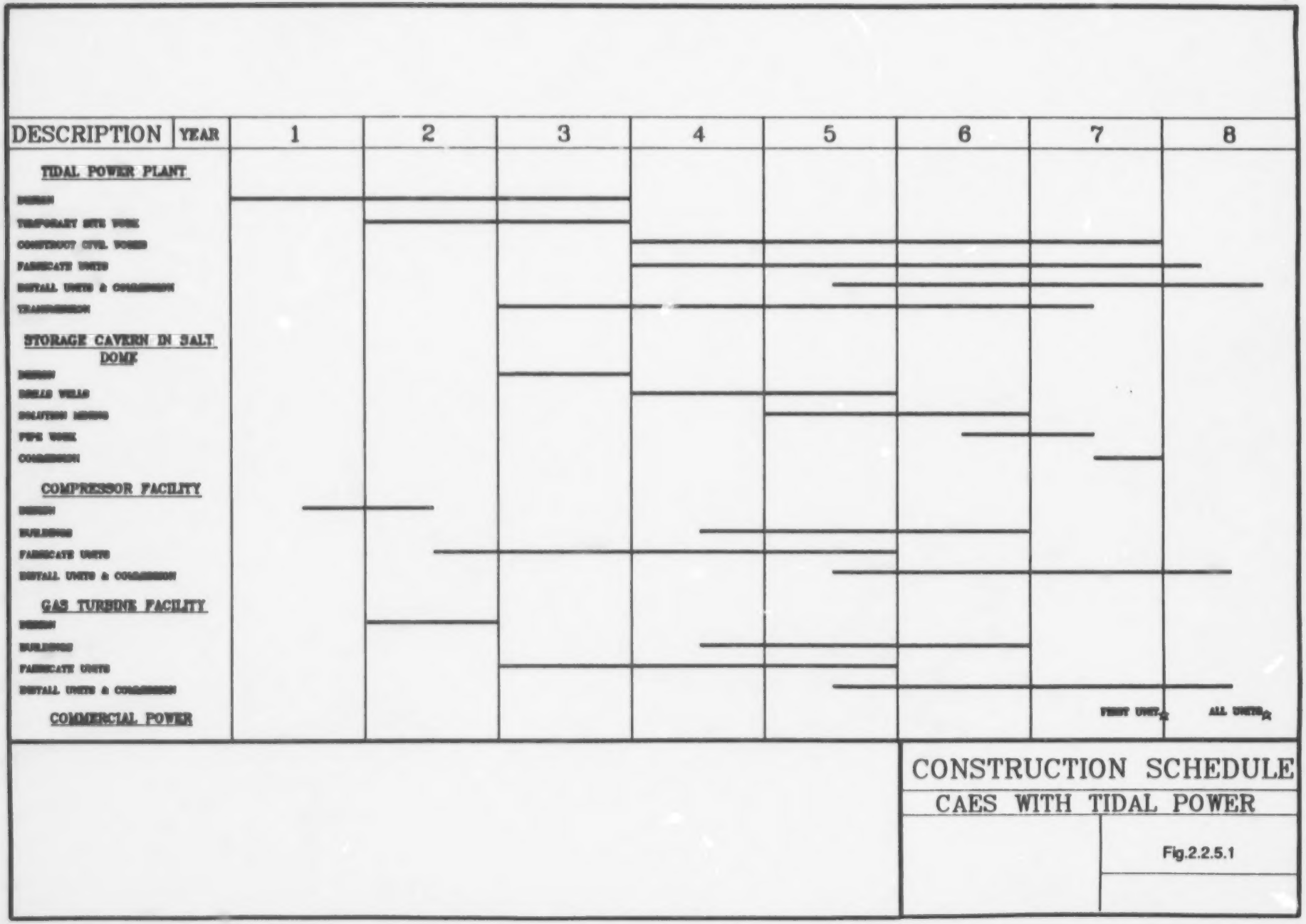
2.2.5.5 - Cash Flow

The cash flow for the CAES facility combined with a tidal power plant is given in Table 2.2.5.8. The cash flow is based on prevalent standard commercial conditions in the market place with regard to advance payments and retention. The cash flow is based on the estimate for the facility given in Table 2.2.5.1 and the schedule presented in Figure 2.2.5.1.

TABLE 2.2.5.8

CASH FLOW
CAES WITH TIDAL POWER PLANT
SCAN DECEMBER 1987 MILLIONS

Description	Year 1	2	3	4	5	6	7	8	Total
Tidal Power Plant and Transmission 42 turbine generator at 34 MW	21.7	189.2	279.3	539.2	743.3	628.1	407.0	110.6	2918.4
Compressor Plant 24-60 MW compressors	8.0	63.0	115.0	147.0	215.0	95.0	70.0	25.8	738.8
Gas Turbine Generator Plant 14-100 MW gas turbine	-	10.0	55.0	130.0	169.0	145.0	35.0	29.8	573.8
Air Storage Facility 13 million m^3	-	-	3.0	20.0	57.0	43.0	7.0	-	130.0
TOTALS	29.7	262.2	452.3	836.2	1184.3	911.1	519.0	166.2	4361.0



CONSTRUCTION SCHEDULE

CAES WITH TIDAL POWER

Fig.2.2.5.1

2.3 - Direct Coupled Turbines and Compressors

In concept the idea of a compressor system driven through a series of speed increasing gear boxes direct from the hydro turbine is a straightforward mechanical system. In practice, it is also possible to achieve a gear system which can indirectly drive a generator and this is done on small standard units. The speed increase from turbine to generator is small and, as the loads are light, right angle drives or incline epicyclic gearing can be used.

Unfortunately, when the unit size increases from 3 to 5 MW to 34 MW and the speed increase involved is from 50 to 75 rpm to 1800 rpm there is no precedent for such equipment. To establish the feasibility of such an advance in gearbox design various suppliers were contacted and their opinions requested.

Responses were received from two major North American manufacturers of gears, using two different approaches. In both cases they were for conceptual designs, only, and such units have not yet been built.

The design basis criteria for the gearbox design was an input speed of 60 rpm, output speeds of 3600 rpm for the low pressure compressor and 9000 rpm for the high pressure compressor, and a maximum input power of 34 MW.

One manufacturer proposed a design using a conventional parallel shaft gearbox which would require triple reuction gears to step-up from 60 to 3600 rpm and quadruple reduction to go from 60 to 9000 rpm. The resulting gearbox would measure about 35 ft long by 30 ft wide and would require gears having a face width of over 5 ft. The manufacturer

has machinery capable of cutting teeth on such gears, but even with the very large equipment currently in use in their plant, all other machining on the gears and housing would probably surpass their capabilities. They also feel transportation of the finished gearbox would be a problem.

The estimated cost of such a gearbox would be 15 times as much as a standard gearbox transmitting the same power through a step-up from 3600 to 9000 rpm, the duty required of the step-up gearbox for a motor driven compressor train.

The other manufacturer proposed a combined epicyclic and parallel shaft gearbox assembly in order to step-up from 60 to 3600 rpm followed by a conventional gearbox from 3600 rpm. The step-up is therefore carried out in 3 stages. The first stage is an epicyclic double reduction gear drive which was ordered by a US municipality but cancelled due to licence problems after engineering had been completed. The application was for a hydroturbine installation rated at 33.2 MW at 56 rpm stepping-up to 514 rpm, and the unit design incorporated the thrust bearing for the runner blade. This design would be used for a 60 rpm to 500 rpm step-up, and the manufacturer proposed a special parallel shaft gearbox combined in one casing with the epicyclic gearbox, for the 500 to 3600 rpm step-up. This special gearbox has not been designed before, although the manufacturer has provided special units with the required torque capacity and ratio. The dimensions of the combined epicyclic and special parallel shaft gearbox assembly would be about 37 ft long by 17 ft wide by 15 ft high, and would cost about 20 times the cost of a 3600 to 9000 rpm conventional gearbox.

A further item of concern with the direct system was the response of the compressore to the variable input power from the tidal turbines. One approach suggested in an earlier report was to drive more than one

compressor per tidal turbine. To remove a compressor from service it was proposed to draw a vacuum on the casing to eliminate most of the aerodynamic drag within and to thereby unload the tidal turbine. However, in the present study it was felt that the added complication of this was best avoided if at all possible, and discussions with suppliers were entered into regarding compressor operating range.
One compressor would be unable to cover the entire range of tidal turbine output power but probably would be able to absorb perhaps 80% of the tidal power. This is achieved by controlling the air flow through the compressors using guide vanes in the axial flow compressor and inlet dampers on the centrifugal flow compressor. The control system would match compressor air flow (and hence power absorbed) with the power available, and reduce compressor flow rate accordingly. In this way, for a given design output pressure, flow and power absorbed could be reduced to a minimum of about 60% of design full load flow. Depending upon the cavern pressure at any particular time, the flow can be reduced still further but at the expense of output pressure. It is therefore possible to utilize a large proportion, but not all, of the tidal turbine power in the direct drive scheme. Careful matching of compressor would be required if the mechanical drive option was followed up in an actual installation.

In summary, it would appear that it is feasible to design and build a gearbox system to transmit 34 MW with a step-up from 60 rpm to 9000 rpm for a single compressor. However, such a unit would be a prototype with the attendant risks and there are other factors which may tend to make this solution unattractive as follows.

- The tidal power generating unit cannot deliver power directly to the grid and as a consequence considerable energy losses would accrue.

- The present design of tidal power house would have to be increased in size significantly to accommodate compressors, gearboxes and ancillary equipment.

- The total power of the tidal turbines could not be used without the complications of multiple compressors for each turbine.

- A greater number of small compressors would be required than for the separate electrical drive system, and a more complex means of controlling each individual compressor control would be required to meet the turbine power variation.

- The compressed air distribution piping system to the underground storage will be more costly to construct than an electrical distribution system.

- The greater number of compressors and the gearboxes increases maintenance, and when coupled to the turbine would mean more potential interruptions to unit operation.

- A much less flexible system would result from this approach, when compared to electrical compressor drives and the possibilities of using direct hydroelectric and/or CAES electrical outage to the grid system.

- A preliminary review of the capital cost of a CAES system utilizing direct coupled equipment indicated that there was unlikely to be a significant reduction in cost.

Based on the foregoing it was concluded that no further consideration should be given to direct coupled turbines and compressors.

2.4 - Effect of Power System Requirements

For the purpose of the initial evaluation of alternative installations it has been assumed that the energy to be supplied to the power system will be the maximum possible constant output over 5 days/week, 12 hours/day based on a monthly mean spring tide energy level. Later on in the study further consideration is given to the implications of this regarding marketability and if any variation could enhance the marketability of the tidal energy.

3 - CAES SYSTEM

3.1 - Geological Aspects

3.1.1 - Introduction

Deep underground cavities are required to store compressed air as part of the CAES system. These cavities may be

- caverns created by underground excavation in appropriate rock formations

- caverns made by solution or dry mining of salt formations

- porous media reservoirs made by water-bearing aquifers or depleted gas or oil fields.

For the CAES system related to Site A8 consideration is given to possible air storage caverns in sedimentary rock at Site A8 igneous rock in the Cobequid mountains and in salt deposits in the Minudie area. Adequate general information is available for each of these formations. Insufficient information is available to allow consideration of storage in porous media reservoirs.

Because of the characteristics of the regional geology the first rock cavern scheme at Site A8 consists of a tunnel complex excavated by tunneling machine in relatively soft rock. The second rock cavern scheme in the Cobequid mountains consists of a large cavern complex excavated in hard rock by drilling and blasting. The salt cavern scheme utilizes large caverns developed by solution mining.

The first two rock cavern schemes are assumed to be hydraulically compensated, that is, with air pressure maintained constant by a head of water. The storage volume required could be of the order of 6 million m^3, including an allowance of 10% for losses in volume with time. The salt cavern scheme is uncompensated, that is with a varying air pressure requiring a storage volume of the order of 13 million m^3, including an allowance of 15% to cover losses in volume due to insoluble deposits and changes with time.

The operating air pressure in the hydraulically compensated caverns is about 4.2 MPa and in the uncompensated caverns between 4.6 and 6.6 MPa. The caverns have to be set considerably deeper than would be required for rock stability alone. Based on rock stress and rock support considerations and a need to minimize the potential leakage of compressed air, an average depth of 600 m is assumed. Each storage cavern scheme is described separately.

3.1.2 - Tunnel Complex in Rock at Site A8

3.1.2.1 - Location

The location of the hydraulically compensated CAES scheme comprising a tunnel complex in rock is at Boss Point on the eastern shore of Cumberland Basin in Nova Scotia. It is close to the east abutment of the dam for the proposed A8 tidal power scheme.

3.1.2.2 - Tunnel Complex and Shaft Layout

The CAES tunnel scheme comprises a deep underground network of north-south and east-west running tunnels. To achieve a storage volume of 6 million m^3 of volume, a number of tunnels in each direction are required; the tunnels are approximately 5 m by 5 m in cross sectional area. Adjacent tunnels are separated by 15 m by 15 m pillars. In plan, the complex will be approximately 1655 m by 1655 m in area and the percentage of rock removed is 44%. Total length of tunnels approaches 240 km. Rock cover over the tunnels is assumed to be 600 m.

Eleven 7-m diameter shafts will be required to achieve the excavation of the tunnel complex in a reasonable period of time of 4 years. During the power generation and compression operations, these shafts serve as either water or air conduits.

The tunnel network will be sloped about 2% to facilitate drainage during construction and the movement of air/water during operations.

3.1.2.3 - Geology

(a) Regional Geology

The regional geology consists of a series of folded and faulted sedimentary rocks of middle to late carboniferous age (300 million years). The

southerly dipping strata are on the northern limb of the Athol syncline, the axis of which trends west-southwest and is located 20 km south of the site area.

In the region the main rock groups, formations and types are as follows in descending order.

Group	Formation	Rock Type
Cumberland	-	Conglomerate, sandstone, siltstone, shale
Riversdale	Boss Point	Sandstone, some shale, siltstone
Canso	Middleborough	Sandstone, siltstone, shale and limestone
Windsor	Windsor A	Salt, some shales, siltstone, overlain and underlain by anhydrite and gypsum
Horton	-	Shale, siltstone. some salt
Basement Complex	-	Igneous, metamorphic rock

(b) Site Geology and Geotechnical Conditions

The proposed CAES tunnel complex is located in the Boss Point Formation of the Riversdale Group which is predominantly sandstone. The strata strike east-west and dip about 30 deg south.

No data on rock strength, in situ rock stress or permeability are available. For this type of rock it can be assumed that the unconfined compressive strength of the sandstone is about 80 MPa. The vertical rock stress is assumed to be equivalent to overburden, i.e., 16 MPa at 600 m depth, and the horizontal stress, 24 MPa, using a k ratio (horizontal to vertical stress ratio) of 1.5, as suggested by the deformation history of the area. It is assumed that the permeability of the rock is of the order of $1x10^{-6}$ cm/s.

No faults are indicated in the site area.

3.1.2.4 - Method of Mining

Since the rock is of relatively low strength, the tunnel complex can be most economically mined by the "roadheader" method, i.e., part face tunneling machine. Several headings could be worked at one time.

The raised height Dosco roadheader with MK 30 head is suggested; this excavates a maximum section with a flat crown (3.56 m wide), a flat floor (5.45 m wide), subcircular walls (6.27 m wide just below mid-height) and a height of 4.83 m.

Removal of the muck is preferably done by rail or small rubber-tired trucks.

The rate of advance at a single heading is estimated at 50 ft/day. This would produce approximately 30 tons or 20 yd^3 of tunnel muck per hour.

To achieve the excavation in say 4 years, several large-diameter shafts will be necessary for the mucking operation.

Sinking of the first shaft will be by drill and blast while the others can be done by the Alimak method (pilot hole up, slash down).

Minor amounts of water are expected during the mining operation.

3.1.2.5 - Rock Support

It is estimated that the average vertical stresses in the pillars after tunneling will be of the order of 29 MPa. Stress concentration will cause the vertical stresses in the pillar walls to vary from the average to about 60 MPa at the mid-point lengthwise and about 90 MPa at the corners. Similarly, horizontal stresses in the tunnel crown will approach 60 MPa. These stresses are significant relative to the unconfined compressive strength of the rock and hence rock bolts will be required in the tunnel crown as well as the corners of the pillars.

Some areas of relatively poor rock may be expected which will require shotcrete application and welded wire mesh on the tunnel crown, as well as the walls. Shotcrete and mesh are estimated to be required over 15% of the total

lineal length of the tunnels. A shotcrete thickness of 100 mm is estimated.

The shafts require shotcrete and mesh for their entire height. A 2 m by 2 m pattern of rock bolts 3-m long may be required over half the length of the shafts.

3.1.2.6 - Reservoir

A surface reservoir is required to contain the compensation water; its volume must be equal to the volume of the underground tunnel complex. A circular reservoir of radius 435 m enclosed by a 12-m high dike and flooded to a depth of 10 m will provide adequate storage. The circumferential length of the dike is 2733 m.

The cross section of the dike comprises a central, symmetrical, compacted, clay till core (3 m wide at top, 15 m at bottom), flanked on both upstream and downstream sides with zones of compacted sand and gravel transition, filter and rain material (average 1.5 m thick), and enclosed by hard, durable, compacted rock-fill shells sloped at 1.8H:1V. A layer of riprap 1-m thick is required on the upstream surface of the rock fill. The top of the structure measures 8 m wide, including the riprap, and the bottom 51.5 m.

It is assumed that the materials can be obtained locally or from the tunnel muck.

3.1.2.7 - Problems and Recommendations

The main concerns regarding the feasibility of the above scheme are the strength, quality and permeability of the rock and its response to water. If the rock is high strength, then a roadheader will be unable to excavate the rock and the drill and blast method will be necessary. This may be more expensive. If the rock strength is very low or if the joint frequency is high, then overbreaking and/or rock instability will occur, requiring more rock support, i.e., more bolts and shotcrete, as well as steel sets, which also leads to higher cost. If the rock is subject to degradation by water, then the scheme is probably not economically feasible; local areas subject to degradation could be treated with shotcrete. If the rock is pervious, that is, allows air leakage, the project is again probably not feasible.

Extensive surface and subsurface explorations, i.e., mapping, drilling, and testing are recommended to determine the feasibility of the CAES tunnel scheme location.

3.1.3 - Caverns in Hard Rock

3.1.3.1 - Location

The location of the CAES scheme comprising large caverns in hard rock is 2 km southeast of the Town of East Mapleton which is 32 km southeast of the proposed A8 tidal power plant.

3.1.3.2 - Cavern and Shaft Layout

The CAES cavern complex would comprise a number of parallel, 300-m long caverns, each with 20 m by 30 m cross-sectional area and spaced at 40 m. The caverns will have arches with a 4:1 span/rise ratio. Total area of the cavern complex is 540 m by 1120 m. The amount of rock extracted is 41%. Total storage volume is 6 million m^3. Rock cover over the tunnels is assumed to be 600 m.

A tunnel 10-m wide and 8-m high will be required joining the base of the caverns at one end. Several 7-m diameter shafts are required to achieve the excavation of the cavern complex in a reasonable period of time of 4 years. During the power generation/compression operations, these shafts serve as either water or air conduits.

The cavern network is to be sloped about 2% to facilitate drainage during construction and movement of air/water during operations.

3.1.3.3 - Geology

(a) Regional Geology

The regional geology consists of a large east-west trending body of igneous granitic rocks which form the Cobequid mountains and which have intruded a series of folded sedimentary rocks north of Cobequid Bay and Minas Basin. On the north, the igneous

rocks are bounded by the lower part of the Cumberland Group and the Boss Point formation which comprise siltstones and shales of late Carboniferous age. On the south there is the Wilson Brook and Diamond Brook formations comprising basalt, siltstone, wacke, and felsic tuff of Silurian and Devonian age. The igneous intrusion is considered to have been emplaced during the Devonian-Carboniferous (340-400 million years) era.

The rock types vary from diroite to granite to granitoid.

(b) Site Geology and Geotechnical Conditions

The proposed CAES cavern complex is located in a granitoid section of the igneous body, just south of the contact with the Cumberland group sedimentary rocks.

No data on rock strength, in situ rock stress or permeability are available. For this type of rock it can be assumed that the unconfined compressive strength of the rock approaches 175 MPa. The vertical stress is assumed to be equivalent to overburden, i.e., 16 MPa at 600-m depth, and the horizontal stress, 19 MPa, using a k ratio (horizontal to vertical stress) of 1.2. It is assumed that the permeability of the rock is less than 1×10^{-6} cm/s. It is assumed the rock quality is good to excellent.

No faults are indicated in the site area.

3.1.3.4 - Method of Mining

Rock excavation of the caverns will probably be by drilling and blasting. Lifts or benches of 7 - 8 m in height will be successively excavated over the full length of the caverns. The upper lift will comprise a central heading followed by slashing out to full width. Several caverns could be underway simultaneously. Removal of the muck is preferably done by rubber-tired trucks.

To achieve the excavation in say 4 years, several large-diameter shafts will be necessary for the mucking operation.

Sinking of the first shaft will be by drilling and blasting while the others can be done by the Alimak method (pilot hole up, slash down).

Minor amounts of water are expected during the excavation.

3.1.3.5 - Rock Support

The average vertical stresses in the pillars are expected to approach 24 MPa after excavation and stress concentration in the vicinity of the walls will cause the vertical stresses to rise to about 48 MPa. In the arch of the caverns, a zone of low compression or even tension may exist. These stresses are generally low relative to the

unconfined compressive strength of the rock; locally minor slabbing (failure) of the rock can be expected however.

Depending on field conditions and assuming high rock quality and the fact that the caverns are not normally open to access by operating personnel during the life of the caverns, pattern rock bolts may be required in some areas of the cavern arches, say 50% of the cavern length, and spot bolting in the remaining area.

Some areas of relatively poor rock, say 5% of the length of the caverns and tunnel, may be expected and will require shotcrete 100-m thick in the arch and walls.

The shafts require welded wire mesh throughout and spot bolts 25-mm diameter and 3-m long. These bolts are estimated to be about 4 bolts per meter of shaft height.

3.1.3.6 - Reservoir

A surface reservoir similar to the reservoir described in Section 3.1.2.6 is required above the cavern complex.

3.1.3.7 - Problems and Recommendations

The main concern in the feasibility of the CAES large cavern scheme is the quality of the rock. It appears very likely that the rock will be of good to excellent quality, but in the event of poorer rock conditions, more rock support will be required.

Extensive surface and subsurface explorations, i.e., mapping, drilling and testing, are recommended to determine feasibility of this CAES scheme.

3.1.4 - Caverns Solution Mined in Salt

3.1.4.1 - Location

The location of the uncompensated CAES scheme comprising caverns excavated in salt is 7.6 km northeast of Boss Point between the east shore of Cumberland Basin and the Hebert River embayment. Boss Point is the east abutment of the dam for the proposed A8 tidal power scheme.

3.1.4.2 - Cavern Layout

The CAES facility mined in salt comprises a number of cylindrical caverns with their axes vertical. The cavern dimensions are 300 m high and 62 m in diameter for a height/diameter ratio of 4.8 to minimize subsidence. Two rows of 7 caverns with a cavern center-to-center spacing of 400 m will provide the total storage requirement of 13 M m^3. Depth of the caverns is given below.

The shaft for the mining and subsequent operation of each cavern is relatively small, usually less than 50 cm in diameter. The actual dimensions must take into account the pipe diameter required to transmit certain air flow rates with minimal friction losses during the power generating period.

3.1.4.3 - Cavern Depth

The required operating air pressures for the CAES caverns ranges from 4.6 to 6.6 MPa.

Minimum rock cover required to contain the air pressure without risk of uplift ranges from 324 m to 467 m, assuming a rock unit weight of 21.2 kN/m^3 and a factor of safety of 1.5.

For the following, a cavern depth of 600 m has been assumed as it appears to correspond to the depth of the main salt body.

3.1.4.4 - Geology

(a) Regional Geology

Reference is made to Section 3.2.4.1 for the regional geology.

(b) Site Geology and Geotechnical Conditions

The proposed CAES caverns are located in the thick marine deposits of bedded salt belonging to the Windsor group. These evaporitic deposits form the core of the east-west trending Minudie anticline which extends from Cumberland Basin, just north of the project site, eastward 55 km to Pugwash, NS. The anticline is very tightly folded and is over-turned to the north. It has been formed as a result

of normal tectonic forces, as well as halokinetic or gravity tectonic forces; the latter cause the salt to flow plastically upwards, displacing adjacent strata, as would a salt dome. As a result of the intense deformation, the salt beds in the central portion of the anticline are thickened and may dip steeply north or south or vertically. Overlying the massive salt body on both sides and top of the anticline is a thick caprock layer of anhydrite and gypsum with some shale and siltstone beds. In the site area in the center of the anticline, the inferred stratigraphy is as follows.

Depth (m)	Material
0 - 600	Anhydrite/gypsum caprock
600 - 4300	Salt with some anhydrite and gypsum
4300 - 4600	Anhydrite/gypsum
4600 - 5200	Shale and sandstone
>5200	Basement complex

The north-south width of the salt body, including caprock at the ground surface in the site area, is, on average, 1500 m. This width is expected to increase with depth, as the anticline spreads laterally. Domtar Chemicals have been solution mining in the Minudie anticline Windsor group salt beds in Nappan (about 15 km east of Site A8) to depths approaching 500 m. Domtar found salt much higher than the 600 m depth quoted above.

Indications are that the salt is very heterogenous, ranging from pure soluble salt to salt mixed with irregular bodies of insoluble anhydrite and gypsum. Other sources suggest alternating layers of anhydrite and salt with as little as 46% salt. Domtar only extract salt where the relative amount of salt is 80% or more. The severely deformed salt shows stratification due to impurities and has a marble-like texture.

Indications are that the salt body is essentially sealed by the overlying mass of anhydrite and gypsum which contains weathered clay and silt in the upper part; no sinkholes occur at the ground surface. Recent uncontrolled mining by Domtar has caused local breaching such that fresh ground water has flooded the cavities in the salt.

The basement complex in the site area is considered to be faulted, but the faults apparently do not extend up into the Windsor group salt beds. However, about 20 km east and southeast, faults do extend to ground surface. These faults are considered inactive.

3.1.4.5 - Present Experience

Solution mining or brining of salt is a common method of extraction. As discussed, this method is presently being used by Domtar Chemicals in the Windsor group salt at Nappan. Domtar has six wells, some of which have cavities up to 120-m wide.

Difficulties have been encountered during the solution mining. Several of the wells were done in an uncontrolled fashion with the result that the cavities migrated up dip and developed unusual shapes. Subsidence has occurred at the ground surface. Caving has caused unstable cavities and loss of drill stems. Masses of anhydrite and gypsum have blocked the solution process. Cavities have enlarged and broken into fresh ground water bodies. Once this happens, it is not necessary to pump down fresh water to perform brining; however, it also causes contamination of groundwater.

The latest solution mining by Domtar has been of a controlled nature and has employed an oil pad which floats on top of the brine and thus prevents the uncontrolled upward cavity migration and allows a preferred and stable shape development.

With respect to other relevant experience, many cavities in salt have now been developed by solution mining in the United States for the storage of fuels at low and high pressure. They are commonly 80 m in diameter and some are 600-m high.

The 290-MW prototype CAES storage facility at Huntdorf in Germany which has been operating since 1978, is considerably smaller than the caverns proposed. The two caverns at Huntdorf in Germany total about 300 000 m^3 of space. Air is stored at a pressure of 7.6 MPa. These caverns were solution mined in a uniform salt dome and the brine was wasted by means of a pipeline to the North Sea.

Air caverns are also used as surge tanks on high head water at hydroelectric projects in Norway. These operate at pressure up to 7.8 MPa.

3.1.4.6 - Method of Mining

A series of telescoping casings will be required to solution mine each cavern. The following casing types are drilled sequentially to the following depths in the initial operation for each cavern.

Casing Diameter (cm)	Drilled Initially to Depth (m)
50	10 m into bedrock
35	600
25	825
18	900

The 35-cm and 50-cm casings are cemented into place to act as a permanent seal. The 18-cm and 25-cm casings are hanging inside and their depths are adjusted to suit during the solution mining operation as described below.

With the 18-cm and 25-cm casings initially set at the above depths, i.e., 75 m apart, fresh water is pumped down the 18-cm casing and brine is removed through the 25-cm casing. (Pumping water down the 25-cm casing and brine removal through the 18-cm casing is also possible, but is likely to result in an unstable inverted pyramid-shaped cavern). Once the cavity is appreciable in size, the oil blanket is pumped into place. Solution mining

with the casings set at the 825- and 900-m depths continues until the first lift is mined out to the full 62-m diameter. Sonar measurements facilitate measurement of the cavity diameter. Once complete, the 18- and 25-cm casings are both lifted 75 m and the second lift is similarly solution mined. The operation continues in this manner until the full 300-m height is mined out.

The brine being removed will have a certain degree of saturation, depending on the rate of circulation and time spent at the various depths. For example, Domtar removes brine which is 26% salt; this reduces the energy required to convert the brine into marketable solid salt. If the brine is not used commercially and is instead wasted, then a lesser degree of saturation is acceptable and faster mining is achieved. Wastage of the brine from the proposed cavern may be facilitated by the proximity of the Cumberland Basin salt water.

As discussed earlier, anhydrite/gypsum can be expected to be irregularly or alternatively distributed in the salt body. It will be necessary to obtain an estimate of the relative amounts of insoluble anhydrite/gypsum and soluble salt. Based on this, a sump positioned at the bottom of the cavern must be designed large enough to accommodate the volume of insoluble material expected; for example, if 10% of the material is insoluble, the cavern must be 1.5 (0.10 by 300 m) or 45 m deeper than the original 300 m. The 1.5 factor is to allow for bulking of the anhydrite/gypsum blocks.

Obviously, if the percentage of insolubles becomes relatively high, much more cavern volume must be solution mined than is necessary for the operation of the CAES cavern.

Once the cavern is complete, the 18-cm and 25-cm casing are removed, leaving the 35-cm and the 50-cm casing in place. The next operation is the removal of the brine in the cavern by means of a submersible pump capable of passing down the 35-cm casing and lifting the brine whose specific gravity will be in the range of 1.2 from a depth of 900 m.

If the pipe diameter required for the air flow exceeds 35 cm, a larger system of casing must be selected and placed. During the design of the brining operation, the supply of fresh water must be considered. It is assumed that an adequate supply of fresh water will be available at little or no cost.

3.1.4.7 - Problems and Recommendations

One concern in selecting the site of the salt cavern air storage, near the proposed tidal power plant at Site A8, is the relative amount and distribution of insoluble anhydrite and gypsum in the salt deposit. Another concern is the tightness of the caprock; indications are that it is tight, but it must be proved. Before final design extensive explorations are required to determine the anhydrite/gypsum content and the tightness of the

caprock. These investigations should also confirm the absence of any active faults in the project area.

Salt tends to creep under certain stress conditions, as would exist in underground caverns. This will need to be investigated at the time of final design to determine if the progressive reduction in cavern volume with time is significant.

A source of fresh water is required for the solution mining.

Alternative CAES cavern sites in bedded salt deposits which are less deformed, more uniform and probably contain less insolubles, may exist 105 km southeast of the present proposed site area. These sites would necessitate long transmission lines to obtain the power from the A8 site.

3.2 - Selected Sites

3.2.1 - General

3.2.1.1 - Location

Potential CAES sites were considered at the general locations described in Section 3.1. Even though the locations are not defined accurately the distances to the sites from various reference points establish the area in sufficient detail to provide some guidance on foundation bearing capacity and services available.

3.2.1.2 - **Rail and Road Access**

None of the sites have direct rail access. The closest rail siding to the Boss Point and Minudie area is Maccan some 21 km east. Any requirement for heavy lifting equipment would have to come from Amherst or elsewhere. A rail line used to run from Maccan to Joggins, a community 5 km south of Boss Point. This line has been abandoned and to reinstate it would require new railway bridges over the Maccan River and at River Hebert. The substructure for the abandoned bridges at both Maccan River and River Hebert are still visible as is the road-bed in the area.

The lack of rail access to Boss Point and the Minudie sites is not the only transportation problem as the two highway bridges over River Hebert and the Maccan River are very old, single lane, truss structures not well maintained. Both are posted to allow 12-ton vehicles at normal speed, and have a vertical clearance of 5 m. The roadway width between trusses is about 3.5 m. Special permits would be required to move heavy loads.

The nearest rail siding to the East Mapleton site is Springhill Junction some 24 km north and east. Again, heavy lifts would require imported machinery. Highway access to the East Mapleton site is complicated by a very sharp entrance turn into the road leading through the area. After entering the East Mapleton road, a very fragile looking, single lane, pony truss type bridge crosses the Southampton River. Heavy loads would not be permitted over the structure without permit and probably

upgrading. The alignment of this bridge is such that it would be difficult to maneuver long loads.

In general, all highways are all-weather except for the road to the Minudie site from the Joggins side where there is a stretch of mud/gravel type road which probably would not support heavy loads except in the dry season.

The magnitude of the construction of the A8 site would probably require an upgrading of access in general. The cost of such upgrading could perhaps be incorporated into the construction of the A8 site rather than the CAES facility. This, of course, would be true only of the Boss Point and Minudie sites.

The transmission line from Boss Point to East Mapleton would be 30 - 35 km in a direct line. From Minudie another 7 - 10 km would be added. The transmission line must cross the River Hebert then to the Southampton area, and probably follow Route 2 towards East Mapleton or through the woods to the site. The tree cover is quite heavy along this line.

3.2.1.3 - <u>Water Supply</u>

The supply of water for pressure equalization and for salt removal at Minudie is difficult to confirm. Most small villages and individual homes in the Boss Point and Minudie area are supplied by drilled or dug wells. The larger towns further east such as Springhill, Oxford and Amherst either trap runoff in lakes or use aquifers found in sandstone or in sand and gravel beds. The Department

of the Environment of Nova Scotia, in their report titled "Regional Water Resources Cumberland County, Nova Scotia", provide an adequate analysis of the potential supply of water for the eastern portion of the county, but do not address the area adjacent to Boss Point or the Minudie sites.

East Mapleton is located in the Cobequid range and approximations of water supply can be derived from the above-mentioned report. A number of brooks and the Southampton River are in the area and could be harnessed to supply water for the CAES plant. The reliable flow available is difficult to assess. Springhill, some 15 km away, is serviced by water from the Leamington Brook watershed. The report on Water Resources states that the Leamington Brook system has a low flow equivalent of 14x10 m^3/d. This watershed is 4.5 km north and east of East Mapleton site and could probably be tapped into.

The Southampton River is also some 5 - 6 km away and it has a rather large drainage area. It should be noted, however, that Springhill will be drawing on the Leamington Brook watershed for any addition to its supply in the future. It would be better, therefore, to concentrate on drilled wells or other watershed areas which drain into the Southampton River. The steady low flow capacity is unknown for these areas as they have not been metered.

Drilled wells analyzed for the western portions of the county up to the Maccan watershed indicate wells are generally 20 m deep and have a yield in the order of

0.34 - 0.64 L/s depending on the aquifer encountered. For the volume of water envisaged for equalization, this would mean numerous wells would be required. It may be more economic to harness the local brooks flowing from the Cobequid Mountains such as Mapleton Brook, Henry Brook and the Southampton River downstream of the Leamington Brook watershed.

The Boss Point site should consider the use of water from the Cumberland Basin. This could be pumped directly from the basin to the reservoir. Because of the solids in the water, special filters may be required to protect pumps and reduce sediment buildup in the reservoir. Clay material is available within 20 km trucking distance of both the Boss Point and East Mapleton sites for the reservoir core construction envisaged.

The Minudie area site would have to be serviced by drilled wells unless water from the basin is acceptable. Again, filtering would be required to reduce wear on machinery (pumps, etc) if this water source is used.

3.2.2 - Site-Specific Comments

The following are comments on the selected sites. The foundation capabilities are based on the soils native to the area and estimates of the probable capacities of these soils.

Boss Point (Site A8)

This site is close to the tidal power plant and bedrock is exposed along the shore and in Lower Cove, some 2 km south of

the site. It is anticipated that the soil cover is shallow with the possibility of founding on bedrock with spread footings.

The closest village to Boss Point is Joggins, some 7 km south. Here medical attention can be provided by doctors but no hospitalization is available. Joggins has a volunteer fire department. The water supply for the village is dug or drilled wells. Very little construction equipment is available in the area. Electric power and telephone service is available.

The closest rail siding to Boss Point is at Maccan, about 25 km east of the site. As noted in the general comments, two highway bridges of questionable capacity govern the transportation of heavy equipment to the site. Maccan does not have a transfer shed at the siding and any heavy handling equipment must be brought in from the Amherst area.

East Mapleton
(area proposed for
hard rock caverns)

The East Mapleton site is quite remote and does not have direct access to medical or firefighting services. Power and telephone lines do feed the homes along the highway. Springhill is the largest town in the area and is 16 km north and east of the site. Springhill has hospital facilities, firefighting equipment and a number of light construction companies. The nearest rail line or siding to the site is at Springhill Junction, 25 km north and east of the site. Heavy equipment lifts would require machinery from Amherst or elsewhere.

As stated in the general comments, the road access from Springhill Junction to the site would require movement through the Town of Springhill, with some sharp turns to be navigated. Once reaching the East Mapleton Road, a very poorly laid out intersection with an extremely sharp turn exists. About 300 mm from the turn is a small pony truss bridge with a single lane. The load capacity of this bridge is suspect and upgrading prior to usage will be required if the loads exceed 12 tons. The space between trusses does not exceed 3.5 m. It would probably be necessary to upgrade or replace the bridge in order to provide good access to the site. This would involve a realignment of the intersection and a new structure. The new span would be in the order of 30 m.

Minudie Site
(area proposed for salt caverns)

The area in which this site has been chosen rests on compacted till. This is a moderately well draining material; however, adjacent to the pockets of this material are others which have poor drainage characteristics. It is quite possible that 0.150 MPa bearing capacity is available in the area. There are no structures in the area except small housing, so it is difficult to predict the actual bearing capacity. It is anticipated that the depth to bedrock is somewhat greater than at the Boss Point site. There is no bedrock outcropping visible from the road.

Joggins, as described for Boss Point, is the nearest town about 9.5 km south and Maccan is the closest rail siding. The road from Joggins to the site has a gravel surface. In the wet

season or in the spring, it would be very poor for heavy load transportation.

3.3 - Developments in CAES Plants

The CAES plant described previously is in effect the current approach to existing or planned installations. It utilizes currently available technology or that which requires minimal development, such as the higher pressure and temperature gas turbine. As mentioned, the regenerator is probably the only component still classed as unproven for CAES applications, but this is a near-term completion development program.

There do not appear to be any significant recent advances in gas turbine or compressor design which would significantly improve the overall performance or economy of the retiming system using CAES. However, recent work carried out on behalf of the Electric Power Research Institute (EPRI) and work in support of currently proposed new projects, has led to optimization of the turbo machinery (compressor/gas turbine) for CAES plant. In particular, the optimizations have revolved around the compression/pressure ratio, in which the selection of optimum compressor train is made on the basis of the affected cost items. These items are

- cavern cost
- compressor energy-consumption cost
- compressor-train installed cost
- heat rejection system capital cost.

Each cost item is affected differently by the compression ratio changes, and while the details of such an analysis is outside the scope

of this report, it is true to say that optimization methods have been developed for six different turbo machinery trains for salt caverns, aquifers and water-compensated caverns. The resulting optimization enables selection and evaluation of the various manufacturers compression equipment on a cost-benefit basis.

In the longer term, developments in CAES plants could revolve around such improvements as recovery of the heat of compression and the use of coal derived fuels. Studies have investigated

- storage of heat of compression in pebble beds or other storage medium for use in heating the air during the expansion cycle to reduce the amount of fuel required

- utilization of fluidized bed combustors to provide coal combustion gases for the gas turbines

- utilization of a coal gasifier to provide combustible fuel gas to the gas turbines.

Studies have shown that each of these technologies have promise. The use of heat storage is considered to be technically feasible in the near term with equipment similar to that currently available, and is economically attractive particularly when storage space such as an abandoned mine is available.

Fluidized beds still require a number of technical areas to be improved, such as hot gas cleanup to avoid gas turbine blades erosion and corrosion.

Coal gasification and use in gas turbines is a developing technology at this time, and the promising performance of the Coolwater project in California indicates a maturing technology which could be applied to CAES if proven economical.

A further possibility to improve the efficiency of the gas turbine and to generate increased power output would be the addition of a steam generator to recover the heat from the gas turbine exhaust. The steam would drive a steam turbine driven generator to provide additional electrical output. This is termed a combined cycle plant and is unquestionably a way of improving the thermal efficiency of the CAES plant using well proven concepts and equipment. It does, however, increase the cost and complexity of the CAES plant and this would require further evaluation.

3.4 - CAES System Layout

On the basis of the foregoing studies the preferred layout of the base case compressed air energy storage (CAES) system for returning tidal power from Site A8 will include the following major components.

(a) Tidal power plant as recommended in the 1984 studies, that is with ebb flow generation using a variable speed turbine generator. Installed capacity is 42 turbines, each rated at 34 MW.

(b) Transformers and DC convertors together with transmission connections to power system and transmission line and substation at the CAES plant.

(c) Electric-driven compressors plant located near the site of the storage cavern. Plant capacity is 24 compressors, each 60 MW, totalling 1440 MW.

(d) Storage caverns located in the salt deposit in the Hebert River. These caverns are solution mined with a total air storage volume of 13 M m^3 including a 15% allowance for insoluble anhydrite and gypsum. The operating pressure range in the caverns is 4.6 to 6.6 MPa.

(e) Gas turbine plant located near the air storage caverns. Plant capacity is 14 units each 100 MW, giving a total of 1400 MW. Fuel has been assumed to be natural gas.

(f) Transformers and DC convertor together with transmission connections to power system.

(g) DC transmission line to Ludlow, Mass. to connect to NEPOOL system.

The base case layout for the CAES system has been selected to provide for direct connection from the tidal power plant to the power system as well as through the compressed air energy storage to the system.

3.5 - Cost/Performance Parameters

Using the base case estimates described in Section 2.2.5, approximate unit costs associated with increasing or decreasing the size of installations for the CAES plant are as follows.

One 60 MW compressor, plus or minus	$18.7 million equivalent to $310,000 per MW
One 100 MW gas turbine, plus or minus	$30.5 million equivalent to $305,000 per MW
Storage in salt dome, plus or minus	$10 million for 1 million m^3 or $10 per m^3 of storage capacity

These unit costs should not be applied to changes in installation exceeding 20% of the base case.

4 - MARKETABILITY

4.1 - Introduction

The system that has been investigated herein is a combination of an ebb-flow tidal power plant with compressed air energy storage in which the energy generated at the tidal power station is stored as compressed air for use in a high-pressure gas turbine. It is the electric energy from the gas turbine which is ultimately fed to the electric supply system. The objective of the analysis is to investigate the economics of the ultimate energy which the Tidal-CAES system can deliver to the electric supply system. The interaction of the tidal power plant and the CAES system has been discussed in Section 2.

In the original proposal, the idea of coupling the tidal turbines in the power plant directly to air compressors had been suggested. This concept was found to be impractical following discussion with manufacturers of equipment and has not been considered in detail.

The analysis provides preliminary evaluation of the economic viability of the Tidal-CAES system as a source of peaking capacity and energy to be supplied to the New England Electric systems.

4.2 - Methodology

In the preliminary economic evaluation of the Tidal-CAES system, 1987 estimates of capital costs for the facilities have been used. Operating and maintenance costs, loss assumptions and other pertinent data have been taken from the 1981 and 1984 studies of Tidal Power in the Bay of Fundy. It is assumed that an appropriate alternative source

for the energy supplied by the Tidal-CAES system is a conventional gas turbine facility. A lower cost energy source for comparative purposes would be a coal-fired thermal plant. However, comparison with the higher energy cost gas turbine plant indicates the potential economic viability of the Tidal-CAES system and considerable additional study would be required to evaluate a specific proposal.

4.3 - Analysis of Tidal Energy and the CAES System

The assessment of the Tidal-CAES system has been described in Section 2. Table 4.1 summarizes the findings of that assessment.

TABLE 4.1

Average Tidal Energy Production (28 days)	267.63 GWh
Storage Requirement	40.00 GWh
Uncompensated Cavern Volume (minimum)	11.2×10^6 m^3
Uncompensated Cavern Volume (adopted) (see Section 2)	13×10^6 m^3
CAES Energy Output (5 day/week, 12 hours/day)	
All Tidal Energy to Storage	85.8 GWh/week
Some Tidal Energy Supplied Direct	78.3 GWh/week
Fuel Input to CAES Turbines	
All Tidal Energy Through Storage	1443×10^{12} J
Some Tidal Energy Supplied Direct	900×10^{12} J

The foregoing are based on the long-term average tidal energy production during a 28-day period and investigation of actual tide samples indicate that month-to-month variability could be 19%.

It should be noted that the output from the gas turbine component of the CAES system is essentially independent of the tidal energy input, particularly if all tidal energy is fed through storage. However, in the subsequent economic analyses, it has been implicitly assumed that the energy output each week is held constant. Significant week to week variations in the total CAES system output would affect the cavern storage requirements.

4.4 - Economic Evaluation

In the analysis, a discount rate of 4.75% has been used through-out. This is the same rate that was used in the "Fundy Tidal Power Update 1981" report to the Tidal Power Corporation, Nova Scotia. All analyses have used constant prices as of late 1987. Each equipment item is amortized over a life that is appropriate for that item.

4.4.1 - Tidal Plant and Transmission Costs

Cash flows for the tidal power project and transmission to Ludlow, Massachusetts were taken from the report to Alcan Aluminium Limited entitled "Fundy Tidal Power-Stage 1" dated December 1984. The annual cash flow pattern was applied to the updated costs prepared during this study. The as-built cost including IDC at 4.75% is estimated to be as follows

	Millions 1987 Prices ($)	
Tidal Power Plant	2008.0	
Interest during Construction	360.0	
Subtotal		2368.0
Transmission and Other	910.4	
Interest during Construction	163.3	
Subtotal		1073.7
Total		3441.7

Assuming the economic lives of the tidal plant and of the transmission system are 50 and 30 years respectively, amortization charges will be $133.79 and $57.00 at an interest rate of 4.75%. Annual costs for of the tidal plant for operation, maintenance and other costs were assumed to be 1% of the tidal plant capital costs or $25.40 million. Annual costs of 0.5% of the capital cost have been assumed for the transmission and other items or $4.51 million. Total annual costs are estimated to be

	Millions 1987 Prices ($)
Tidal Power Plant	133.79
Transmission and other	57.00
O & M costs	29.91
Total	220.70

4.4.2 - CAES Costs

The CAES part of the system consists of three main components, the compressor station, the storage caverns and the high-pressure gas turbines. For costing purposes, a compressor station capacity of 1440 MW has been assumed and a gas turbine capacity of 1400 MW. Both these capacities are greater than the minimum requirements for the system. However, the total installed capacity at the tidal plant will be 1428 MW and for energy production estimates, allowing for maintenance at the tidal plant, only 1326 MW has been assumed available. It is appropriate to assume that some redundancy would also be provided in the compressor station. With respect to the gas turbine capacity, it has been noted in Section 4.3 that the total energy suppliable through the Tidal-CAES system is independent of the pattern of the demand. Hence, more or less capacity might be installed to provide specific peaking requirements. The significance of the cost of the installed capacity has been assessed in the sensitivity analyses described in Section 4.4.4.

It has been assumed that the storage would be provided through solution mining of the salt deposits as this appears to be the least cost solution. The capital costs of the CAES components together with an estimate of interest during construction are as follows.

	Millions 1987 Prices ($)
Storage Cavern Construction	130.00
Interest During Construction	21.39
Subtotal	151.39
Compressor-Turbine System	1312.60
Interest during Construction	249.00
Subtotal	1561.60
Total	1713.00

Assuming economic lives of 50 years for the storage caverns and 25 years for the compressor-turbine system, annual capital charges would be $7.97 and $108.04 million respectively. Operating and maintenance costs for the storage caverns are difficult to estimate but an allowance of 2% of the capital cost has been assumed or $3.03 million per year. Fixed annual operating and maintenance costs for conventional gas turbines are approximately 1% of the capital cost. However, as the equipment proposed for the CAES is more specialized, higher costs might be expected. As a base case, 2% of the capital cost has been assumed or $31.23 million per year. Total annual costs are therefore

	Millions 1987 prices ($)
Storage Caverns	7.97
Compressor-turbines	108.04
O & M Costs	34.26
Total	150.27

Total annual fixed costs for the Tidal-CAES system (either scheme) are $370.91 million.

4.4.3 - Alternative Gas Turbine System

It has been assumed that the alternative to the Tidal-CAES system would be conventional gas turbines located close to the load centers in New England. Accordingly, there would be no significant transmission associated with them. Based on recent quotations for similar gas turbine installations, an installed cost of $700 per kW is recommended including IDC. Using 1400 MW installed capacity as comparable to the installation at the CAES system, the total capital cost of the alternative system would be $980 million. Assuming an economic life of 25 years, the amortization charge would be $67.80 million. Total annual operating and maintenance costs have been assumed to be $6.3 million. The total annual fixed costs are therefore $74.10 million.

4.4.4 - Results

Variable operating costs for both the Tidal-CAES system and the alternative conventional gas turbines are principally fuel and the future price of fuel is very uncertain. In order to overcome the difficulty of predicting the future price of fuel, it would be useful to determine the price of fuel at which the Tidal-CAES system can compete with the alternative. The results of such an analysis can be compared with the current prices of fuel in the New England states and a primae facea case made for economic viability.

The available energy at site from the all storage scheme based on the Alcan 1984 tidal energy input of 66.9 GWh/week, is 85.8 GWh per week. Fuel consumption is therefore 361×10^9 kJ per week or $18\ 760 \times 10^9$ kJ per year.

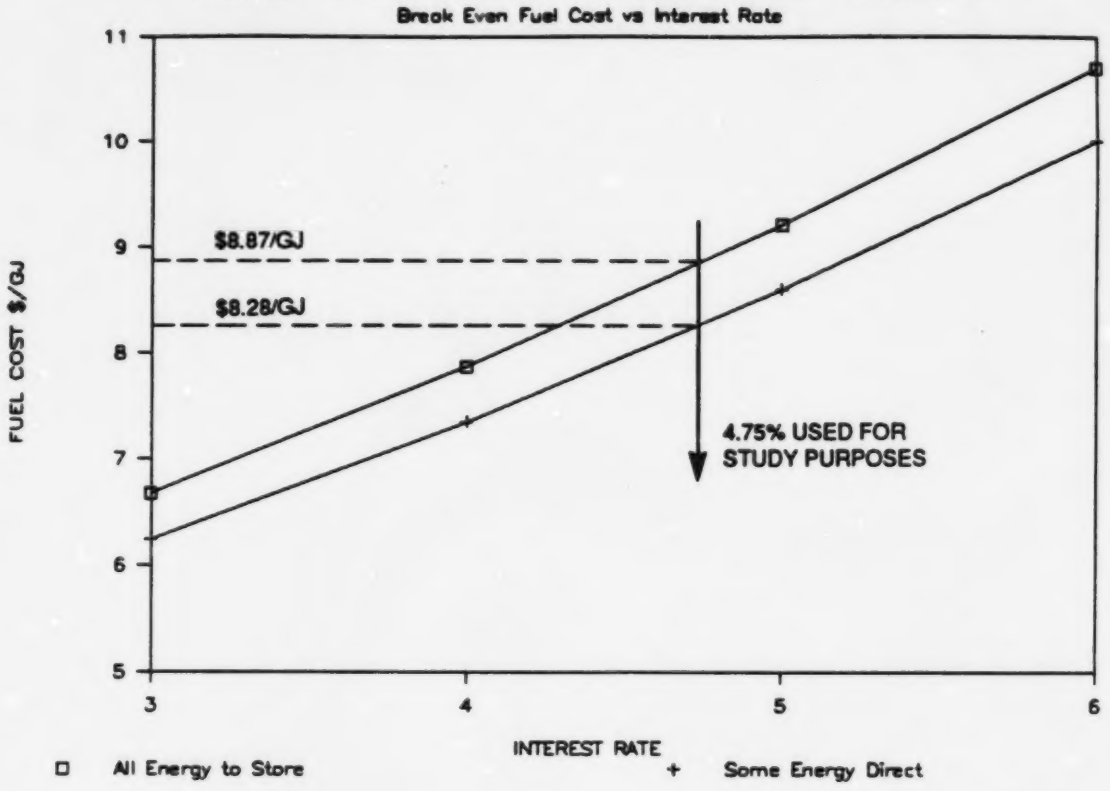
Using the same energy production in the alternative conventional gas turbine, less 3.5% transmission losses for the tidal power, and assuming 12 140 kJ per kWh, the annual fuel consumption would be $52\ 280 \times 10^9$ kJ.

If the Part Direct Scheme is considered, the annual energy output would be 4095 GWh and the annual fuel consumption would be $12\ 124 \times 10^9$ kJ (see Table 4.1).

For the energy supplied through either the Tidal-CAES system or the conventional gas turbine to be equal, the cost of fuel for each would have to be \$8.87/GJ if all the tidal energy is routed through storage or \$8.28/GJ if some tidal energy is supplied directly to the system. These findings are illustrated in Figure 4.1 which shows how the breakeven fuel cost varies with discount rate. Higher discount rates detract from the more-intensive Tidal-CAES system so that the breakeven fuel cost rises with discount rate.

A brief review of fuel prices in the Boston area suggests that the current price for one GJ of natural gas is about \$7.00 to \$7.20 Canadian. Liquid fuel prices are generally lower at about \$4.50 to \$4.75 per GJ.

TIDAL–CAES vs ALTERNATE GAS TURBINE



This figure shows how the break-even fuel cost is affected by the real interest rate used in the analysis.

The analysis is based on a comparison between

- tidal power generated on the Bay of Fundy, retimed using a Compressed Air Energy Storage plant and transmitted to New England
- a gas turbine plant installed in the New England market area with a heat rate of 12.14 kJ/kW·h (11 500 Btu/kW·h).

The capital cost for tidal power generation used in the above figure is defined in Section 2. The gas turbine plant has a capital cost of $700/kW.

Fig. 4.1

CANADIAN ATLANTIC POWER GPOUP LTD
ENERGY MINES AND RESOURCES CANADA
RETIMING TIDAL POWER USING CAES

BREAK-EVEN COST ANALYSIS, SENSITIVITY TO REAL INTEREST RATE

CAPG

Given the foregoing costs of fuel, the Tidal-CAES system would not likely be attractive at the current time. Future fuel prices are imponderable over the short and intermediate term and there are as many different opinions available as people who make them. However, almost all forecasts suggest that within 10 to 15 years, the cost of fuels will have risen significantly and only the timing of such increases is very uncertain.

4.4.5 - Sensitivity Analyses

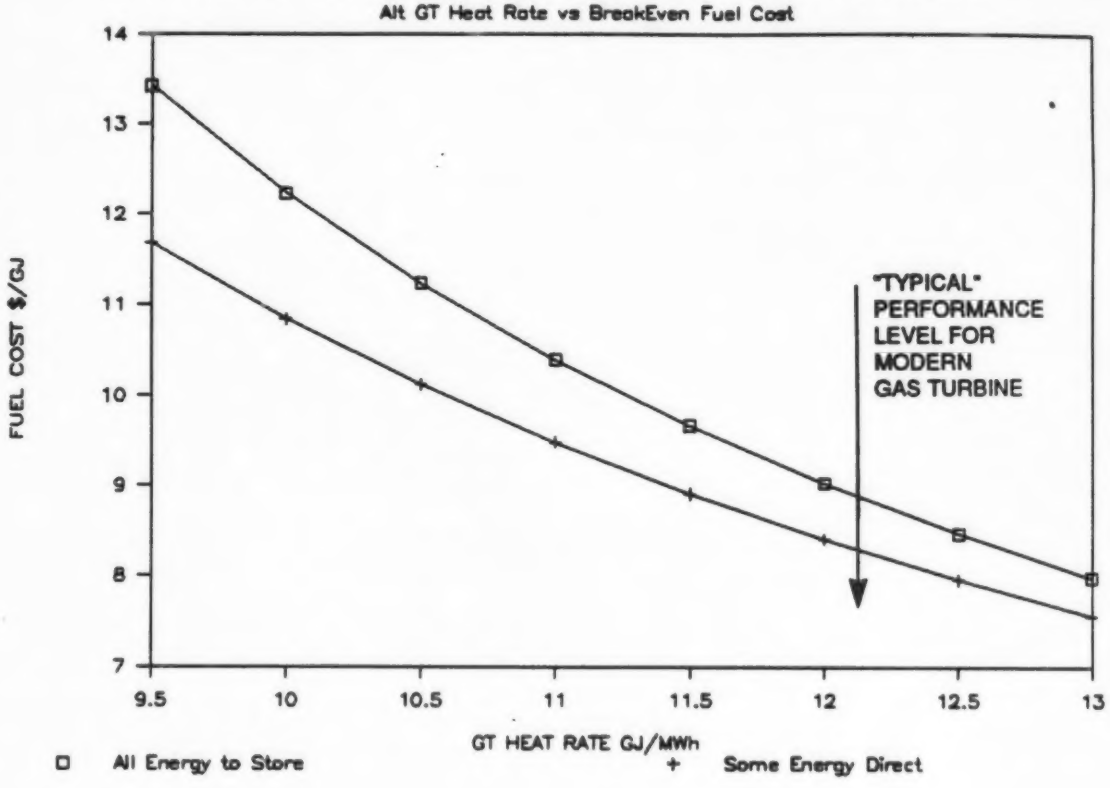
Many of the basic assumptions made in the foregoing sections are uncertain and it is useful to identify how the basic findings in 4.4.4 would be affected by changes in costs and parameters.

Figure 4.2 illustrates the implications on the breakeven fuel cost of a wide range of assumptions regarding the efficiency of the conventional gas-turbine alternative. Some uncertainty exists for this parameter because the efficiency varies with unit duty cycle. Any decrease in efficiency (increase in heat rate) would reduce the breakeven fuel price.

Figures 4.3 and 4.4 illustrate the implications of very wide variations in the cost of the tidal plant and of the CAES system respectively. As would be expected, variations in the tidal plant cost has a much greater influence as those costs represent about 60% of the Tidal-CAES system.

Figure 4.5 presents the at-site, unit cost of energy produced by the Tidal-CAES system for a range of fuel costs.

TIDAL–CAES vs ALTERNATE GAS TURBINE



This figure compares

- tidal power generated on the Bay of Fundy, retimed using a Compressed Air Energy Storage plant and transmitted to market in New England

- a gas turbine plant installed in the New England market area.

The fuel cost for power from the gas turbine to break-even with the tidal power is calculated. For tidal power costed using data presented in Section 2, and a real interest rate of 4.75%.

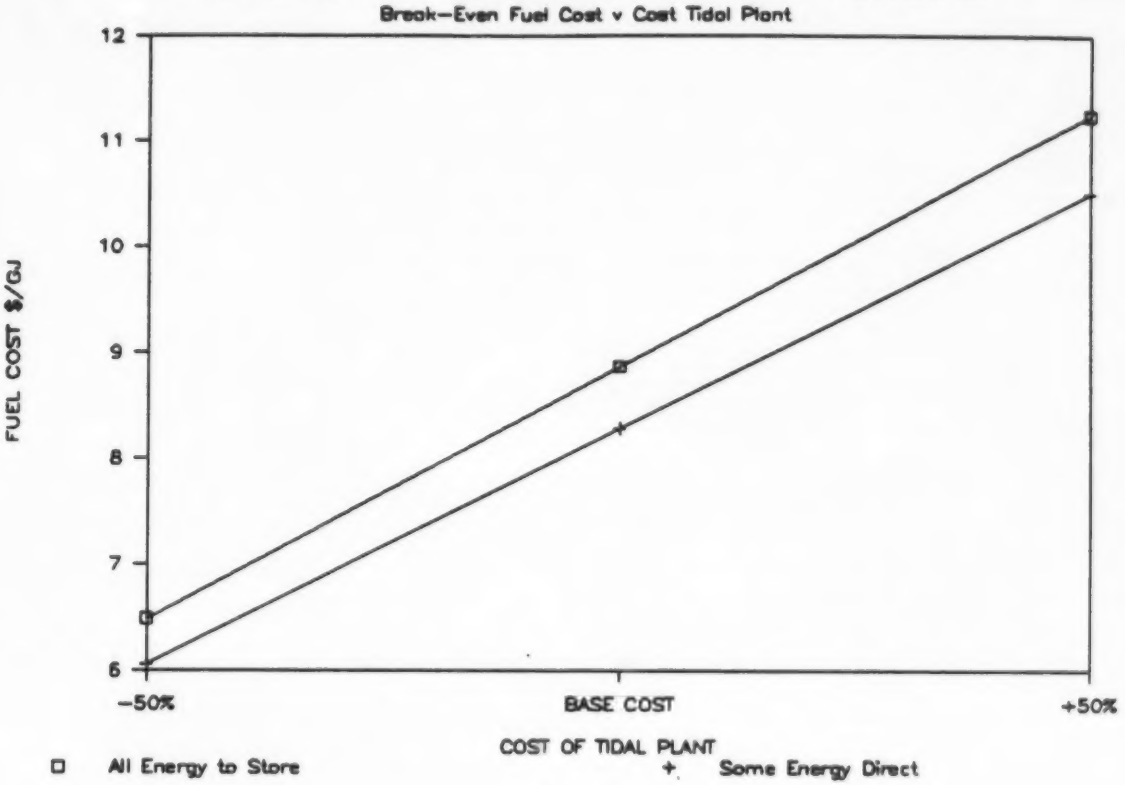
Fig. 4.2

CANADIAN ATLANTIC POWER GPOUP LTD
ENERGY MINES AND RESOURCES CANADA
RETIMING TIDAL POWER USING CAES

BREAK-EVEN COST ANALYSIS,
TIDAL-CAES COMPARED TO GAS TURBINE GENERATOR AT MARKET

CAPG

TIDAL–CAES vs ALTERNATE GAS TURBINE



This figure shows how the break-even fuel cost is affected by changes in the investment cost in the tidal plant (barrage, sluices, powerhouse, turbines, generators). Transmission costs are included in the analysis but not in the sensitivity test. The analysis is based on a comparison between

- tidal power generated on the Bay of Fundy, retimed using a Compressed Air Energy Storage plant and transmitted to New England
- a gas turbine plant installed in the New England market area with a heat rate of 12.14 kJ/kW h (11 500 Btu/kW h).

A real interest rate of 4.75% is used. The capital cost for tidal power generation used in the above figure is defined in Section 2.
The gas turbine plant has a capital cost of $700/kW.

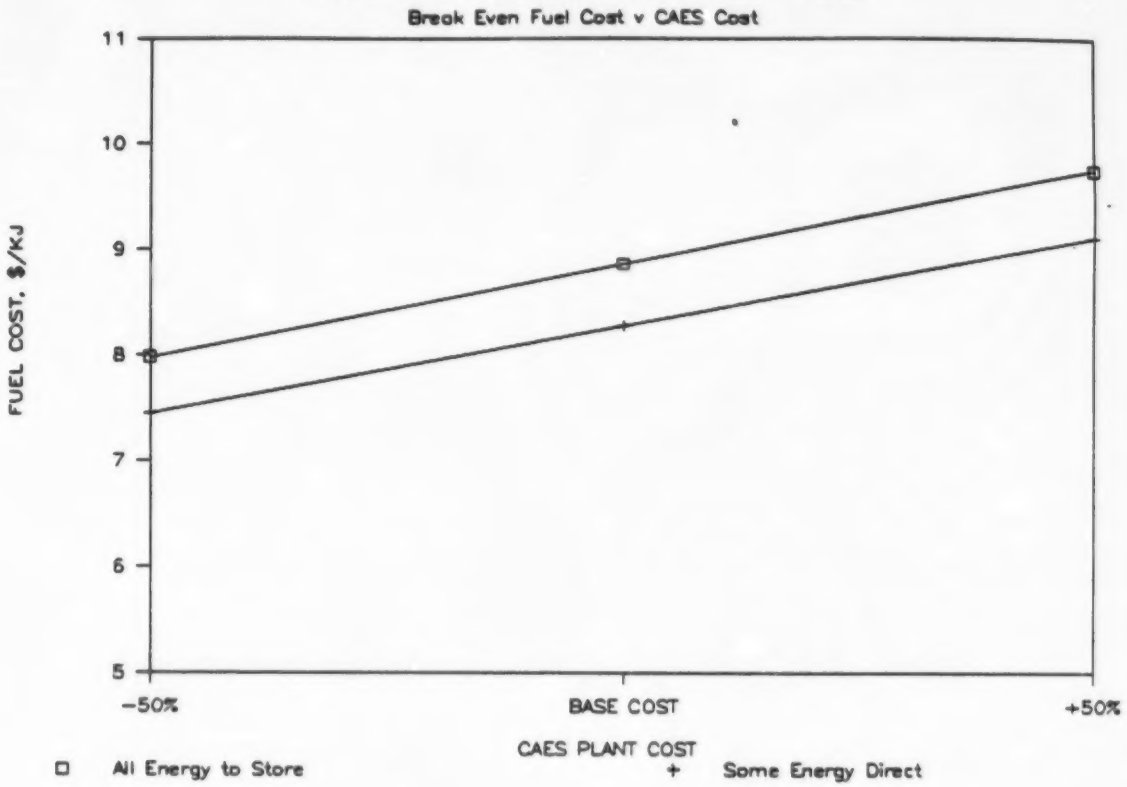
Fig. 4.3

CANADIAN ATLANTIC POWER GPOUP LTD
ENERGY MINES AND RESOURCES CANADA
RETIMING TIDAL POWER USING CAES

BREAK-EVEN COST ANALYSIS, SENSITIVITY TO COSTOF TIDAL PLANT

CAPG

TIDAL–CAES SENSITIVITY TEST



This figure shows how the break-even fuel cost is affected by changes in the investment cost in Compressed Air Energy Storage plant costs (compressors, storage cavern, expansion turbines and associated motors and generators). The analysis is based on a comparison between

- tidal power generated on the Bay of Fundy, retimed using a Compressed Air Energy Storage plant and transmitted to New England
- a gas turbine plant installed in the New England market area with a heat rate of 12.14 kJ/kW·h (11 500 Btu/kW·h).

A real interest rate of 4.75% is used. The capital cost for tidal power generation used in the above figure is defined in Section 2. The gas turbine plant has a capital cost of $700/kW.

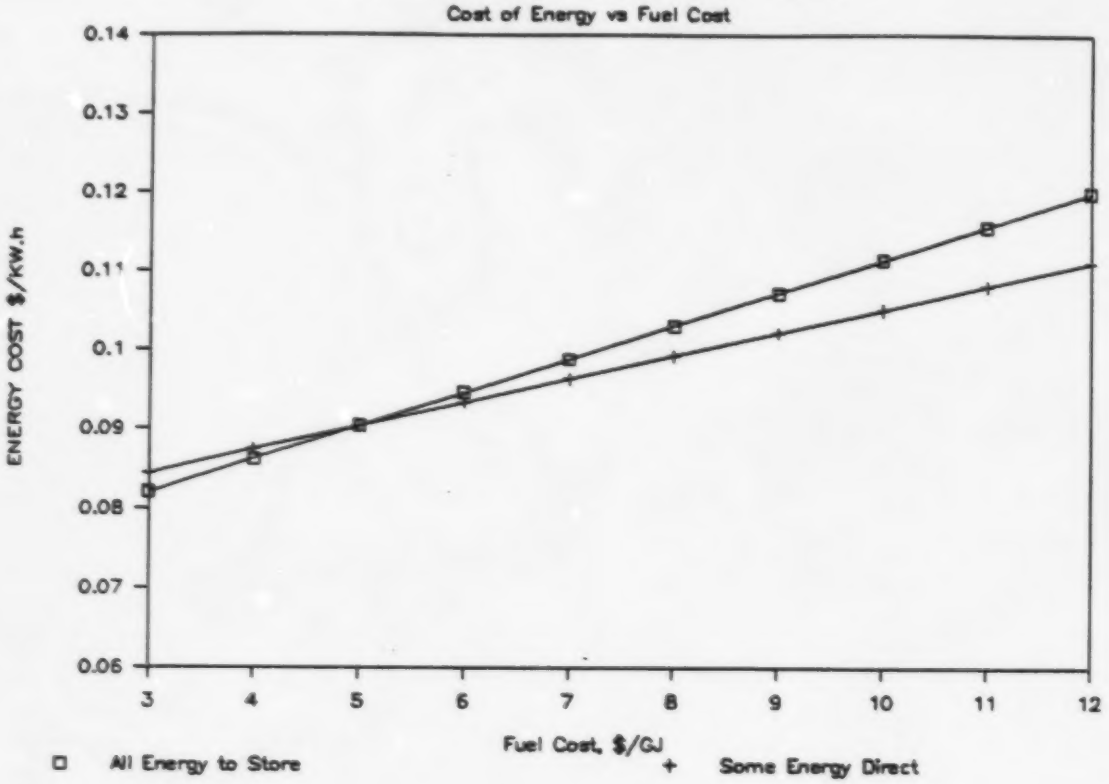
Fig. 4.4

CANADIAN ATLANTIC POWER GROUP LTD
ENERGY MINES AND RESOURCES CANADA
RETIMING TIDAL POWER USING CAES

BREAK-EVEN COST ANALYSIS, SENSITIVITY TO COST OF CAES PLANT

CAPG

TIDAL–CAES ENERGY COST



This figure shows the cost of energy from tidal power, in the Bay of Fundy area, after retiming using a Compressed Air Energy Storage plant. Cost of transmission to the market is excluded from the energy cost.

The figure shows that the retimed power cost is less sensitive to fuel costs if power is marketed directly from the tidal generators (i.e., not routed through storage) when supply is coincident with demand.

The capital cost for tidal power generation used in the above figure is defined in Section 2.

Fig. 4.5

CANADIAN ATLANTIC POWER GROUP LTD
ENERGY MINES AND RESOURCES CANADA
RETIMING TIDAL POWER USING CAES

RE-TIMED ENERGY COST AT SOURCE, SENSITIVITY TO COST FUEL

CAPG

4.4.6 - Availability of Storage

To develop the CAES system, as proposed, to its maximum capacity, the compressed air storage is full to maximum pressure at least once a month and at other times the volume varies in accordance with tidal cycles and load demand. This means that use of the storage by utilities to store surplus energy would be intermittent although reasonbly predictable. Such use would also require additional compressors and gas turbines to develop the required capacity. Since this equipment is specialized and more expensive than conventional gas turbine generators it is unlikely to be economically attractive to the utilities.

5 - CONCLUSIONS

Conclusions resulting from the study are as follows.

(a) It is feasible to retime tidal power from Site A8 using a compressed air energy storage system based on readily available equipment and methodology. The preferred system is to use separate electrically-driven compressors and gas turbine generators with variable pressure or uncompensated underground air storage. An appropriate site for underground storage exists within a reasonable distance of the tidal power plant.

(b) Based on prefeasibility level cost estimates the construction cost of a compressed air energy storage system to provide approximately 1200 MW of retimed power 12 hours/day, 5 days/week is estimated to be $1,442.6 million (1987 dollars). This cost is additional to the estimated cost of $2,918.4 million for construction of the 1428 MW tidal power plant at Site A8 and transmission line to New England.

(c) Improvements in equipment performance and increases in unit sizes of CAES equipment can be expected to reduce the construction cost in the future. However, the greater cost of the tidal power plant has a correspondingly greater effect on the cost of energy.

(d) It is unlikely that direct coupled turbines and compressors will reduce construction cost of the CAES system significantly. When this is considered in conjunction with the lack of operational flexibility of such a system and the unprecedented requirements for low to high speed gears it is concluded that the direct coupled equipment should not be considered further.

(e) The marketability of the retimed power is dependent upon its economic attractiveness compared to alternative methods of power generation that are available.

This comparison has been achieved by calculating the break-even cost of fuel at which the cost of retimed power is equal to that from a conventional gas turbine. For the energy supplied either way to be equal the cost of fuel for each would have to be $8.87/GJ if all tidal energy is routed through storage or $8.28/GJ if some tidal energy is supplied directly to the system. Variation in such items as discount rates will affect the break-even fuel cost. These values compare to current prices in the Boston area of $7.00 to $7.20 per GJ for liquid fuels.

(f) The break-even cost of fuel is not too sensitive to changes or refinements in cost of the CAES plant. Even a 50% change in cost will only cause a 10% change in the break-even cost of fuel. Percentage changes in cost of the tidal power plant have potentially greater impact as it represents 67% of the total construction cost for the CAES-Tidal plant system.

(g) The use of the compressed air energy system as proposed to provide additional storage for surplus energy from utilities is unlikely to be economically attractive.